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Performance analysis and enhancements of packet forwarding in LTE

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Espoo, Aug, 2009

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ABSTRACT OF MASTER'S THESIS

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At handover between base stations in Long Term Evolution (LTE), data is forwarded from a source eNB to a target eNB. The mechanism for handling the packet forwarding is specified in Third Generation Partnership Project (3GPP) Release 8 specifications. The goal of the thesis is to analyse, evaluate and improve the packet forwarding mechanism. The techniques to reduce the amount of forwarded data in the downlink will be studied as a part of the thesis. Such enhancements include modifications to the Radio Link Control (RLC) protocol, as well as improved interactions with other layers, most notably Packet Data Convergence Protocol (PDCP) and Radio Resource Control (RRC). Performance criteria considered for evaluating these techniques include the PDCP buffer size at the source eNB, uplink RLC status load and user object bit rate.

The thesis recommends the LTE network to poll the UE more frequently during the ongoing handover scenarios, compared to the case when handover is not ongoing. This allows the source eNB to be as up to date to the UE reception state as possible, and thus reduces the number of unacknowledged PDCP SDUs to be forwarded to the target eNB. Based on the simulation results, this proposed technique proves to be the most efficient in terms of lower PDCP buffer size at the source eNB, lower uplink RLC status load and higher user object bit rate.

Keywords: data forwarding, handover, LTE, PDCP, RLC
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Abbreviations and Acronyms

1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
3GPP	Third Generation Partnership Project
AM	Acknowledged Mode
AMC	Adaptive Modulation and Coding
AMPS	Advanced Mobile Phone Service
AQM	Active Queue Management
ARQ	Automatic Repeat Request
AS	Access Stratum
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
CCCH	Common Control Channel
CDMA	Code Division Multiple Access
CN	Core Network
CP	Control Plane
CQI	Channel Quality Indicator
C-RNTI	Cell Radio Network Temporary Identity
DAB	Digital Audio Broadcast
DCCH	Dedicated Control Channel
DECT	Digital Enhanced Cordless Telecommunications
DHCP	Dynamic Host Configuration Protocol
DL	Downlink
DL-SCH	Downlink Shared Channel
DRB	Data Radio Bearer
DRX	Discontinuous Reception
DTCH	Dedicated Traffic Channel
DVB	Digital Video Broadcast
EDGE	Enhanced Data rates for GSM Evolution
eMBMS	Enhanced Multimedia Broadcast/Multicast Service

eNB	E-UTRAN NodeB
EPC	Evolved Packet Core
EPS	Evolved Packet System
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
GERAN	GSM Evolution Radio Access Network
GPRS	General Packet Radio Services
GSM	Global System for Mobile Telephony
HSDPA	High Speed Downlink Packet Access
HSUPA	High Speed Uplink Packet Access
IEEE	Institute of Electrical and Electronics Engineers
IMT-2000	International Mobile Telecommunications-2000
IP	Internet Protocol
ITU	International Telecommunication Union
LTE	Long Term Evolution
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MMS	Multimedia Messaging Service
MR	Measurement Report
MU-MIMO	Multi-User MIMO
NAS	Non-Access Stratum
NMT	Nordic Mobile Telephony System
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak to Average Power Radio
PBCH	Physical Broadcast Channel
PCCH	Paging Control Channel
PCH	Paging Channel
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PDSCH	Physical Downlink Shared Channel
PDU	Protocol Data Unit
P-GW	Packet Data Network Gateway
PRACH	Physical Random Access Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality Of Service
QPSK	Quadrature Phase Shift Keying

RACH	Random Access Channel
RAN	Radio Access Network
RFPA	Radio Frequency Power Amplifier
RLC	Radio Link Control
RRC	Radio Resource Control
RRM	Radio Resource Management
SC-FDMA	Single Carrier Frequency Division Multiple Access
SDMA	Spatial Division Multiple Access
SDU	Service Data Unit
S-GW	Serving Gateway
SMS	Short Message Service
SON	Self Organizing Networks
SRB	Signaling Radio Bearers
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TM	Transparent Mode
TTI	Transmit Time Interval
UE	User Equipment
UICC	Universal Integrated Circuit Card
UL	Uplink
UL-SCH	Uplink Shared Channel
UM	Unacknowledged Mode
UMTS	Universal Mobile Telecommunications System
UP	User Plane
USIM	Universal Subscriber Identity Module
WAP	Wireless Application Protocol
WCDMA	Wideband CDMA

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Chapter 1

Problem Definition

The LTE radio interface for 3GPP Release 8 was specified recently. The result of the 3GPP standardisation effort is the evolved packet system (EPS) that consists of the core network part, the evolved packet core (EPC) and the radio network evolution part, the evolved UTRAN (E-UTRAN), also known as LTE. A Base station in case of LTE is called an enhanced NodeB (eNB). During handover between eNBs in LTE, data is forwarded from a source eNB to a target eNB. The forwarded data is finally sent to a User Equipment (UE) by the target eNB on the handover completion. Data forwarding plays an important role from the end user's quality of service perspective. It is important that the handover occurs smoothly with the excellent user experience. The mechanism for handling the packet forwarding is specified in 3GPP LTE Release 8 specification during which all the unacknowledged PDCP Service Data Units (SDUs) are sent from the source eNB to the target eNB. Of these forwarded PDCP SDUs, many will be discarded by the target eNB, as the UE has already received some of these PDCP SDUs, as a fact which could be indicated in a PDCP Status report. If the PDCP Status report is not sent by the UE, then PDCP SDUs will be sent from the target eNB to the UE. The UE may discard these SDUs if it has already received them from the source eNB.

The goal of the thesis is to find methods to decrease the data forwarding from the source eNB to the target eNB and also evaluate the achievable gains. This will not only reduce the unnecessary load on the X2 interface connecting the two eNBs, but also on the radio link between the UE and the target eNB. Moreover, the handover delay will be reduced and the quality of service experienced by the user during the handover will be improved as a result. The scope of the thesis is limited to the forwarded data in the downlink, not considering the uplink data to be re-transmitted by the UE to the target eNB after the handover.

Chapter 2

Mobile Communication History and Evolution

The evolution roadmap of radio communications [9] from the first experiments done by Guglielmo Marconi in the 1890s to the present advanced mobile telephony system has been quite long. To understand the present, complex 3G mobile-communication system, it is important to understand its evolution right from the beginning. Cellular system has evolved from an expensive technology for a selected few individuals to today's global mobile communication system.

AT&T started the first commercial car-borne telephony service in 1946, which was approved by US Federal Communications Commission (FCC). It was also the one, who introduced the cellular concept of reusing radio frequencies, which formed the basis to all subsequent mobile communication systems. Commercial mobile telephony continued to be car-borne, for many years because of bulky and power-hungry equipment.

The analog Nordic Mobile Telephony System (NMT) was the first international mobile communication system. NMT was introduced in the Nordic countries in 1981, at the same time as analog Advanced Mobile Phone Service (AMPS) was introduced in North America. These analog cellular systems are also known as the First Generation (1G) of mobile communication system. They supported telephony services based on voice. It still had problems such as bulky mobile equipment and inconsistent voice quality with the cross-talk between users. The concept of Roaming, came with an international system such as NMT, offering a service also for users traveling outside the area of their home operator. This gave a larger market for mobile phones, attracting more companies into the mobile communication business.

With the advent of digital communication during the 1980s, the interest in developing a successor to the analog communication system materialized and provided the foundation towards the evolution of the Second Generation (2G) of mobile communication system. With a digital technology, came an opportunity to increase the capacity of the system, give a more consistent quality of the service, and develop truly mobile devices. Global System for Mobile Telephony (GSM) project was started to develop a pan-European mobile-telephony system. After evaluations of Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA), and Frequency Division Multiple Access (FDMA) based proposals in the mid-1980s, the final GSM standard was built based on TDMA.

GSM standards were based on narrowband, targeting the lowbandwidth voice services. With the 2G digital mobile communication, came also the opportunity to provide data services over the mobile communication network. The primary data services introduced in 2G were short message service (SMS) and circuit-switched data services enabling e-mail and other data applications. The peak data rate in 2G was initially 9.6 kbps. Packet data over cellular systems became a reality, during the second half of the 1990s, with the introduction of General Packet Radio Services (GPRS) and is referred to as 2.5G. GPRS supported the data rate of 56-114 kbps.

Wireless evolution continued further towards the Third Generation (3G) of mobile communication system. International Mobile Telecommunications-2000 (IMT-2000), also known as the 3G, is a family of standards for wireless communication defined by the International Telecommunication Union (ITU). It includes Enhanced Data rates for GSM Evolution (EDGE), Universal Mobile Telecommunications System (UMTS), CDMA-2000, Digital Enhanced Cordless Telecommunications (DECT) and WiMAX. Of these 3G systems, UMTS is seen as the most widely deployed system in the present world. UMTS is based on Wideband CDMA (WCDMA). With the advent of 3G came the possibilities for a range of new high rate data services that were only hinted at with 2G and 2.5G.

3G evolution is driven by the demands for the lower latency, higher data rates and capacity. UMTS offered a peak data rate of 384 kbps. With the introduction of High Speed Downlink Packet Access (HSDPA) in UMTS, the downlink peak data rate was increased to 14 Mbps. Since there was also a demand for the faster uplink, enhanced uplink was added, which is also referred to as High Speed Uplink Packet Access (HSUPA), with peak data rate of 5.8 Mbps. The combination of HSDPA and HSUPA is commonly referred to as HSPA. HSPA technology is presently evolving in 3GPP, under the name Evolved HSPA and supports the downlink peak data rate of 42 Mbps and uplink peak data rate of 22 Mbps.

The latest step being studied and developed in 3GPP is an evolution of 3G towards an evolved radio access referred to as the LTE and the LTE-Advanced [10]. LTE-Advanced is seen as a candidate for the future Fourth Generation (4G) of mobile communication system. It is expected that deployment of the LTE systems will commence, by the end of the year 2009-2010. LTE will bring improved support and performance for a real-time conversational and interactive services, as it is based on technologies like Orthogonal Frequency Division Multiple Access (OFDMA), Multiple Input Multiple Output antennas (MIMO), higher order adaptive modulations, architectural design supporting lower latency and higher spectral efficiency. Figure 2.1 depicts the evolution of the wireless systems starting from 1G to the future 4G system.

People can already browse the internet or send e-mails using HSPA-enabled notebooks, replace their fixed DSL modems with HSPA modems or USB dongles and send and receive video or music using 3G phones. With LTE, the user experience will be even better. LTE will also enhance more demanding applications such as interactive TV, mobile video blogging, advanced games and professional services. "All IP" is the buzzword in the present telecom industry. More and more people are talking of IP telephony in the home and at their work place. Usage of wireless data services is growing faster than ever before, moving us forward towards the age of mobile broadband. Both, the IP based Internet and the circuit switch based traditional telecom networks are getting converged and moving towards the all IP based wireless networks. The evolution towards all IP based wireless networks has enabled the service developers to develop IP based services, that only the imagination and technology sets limits to. All these combinations of services point towards the applications and services that consume higher data rates and require lower delays compared to what today's mobile-communication system can deliver. While demand for applications such as SMS, Web and Wireless Application Protocol (WAP) access, Multimedia Messaging Service

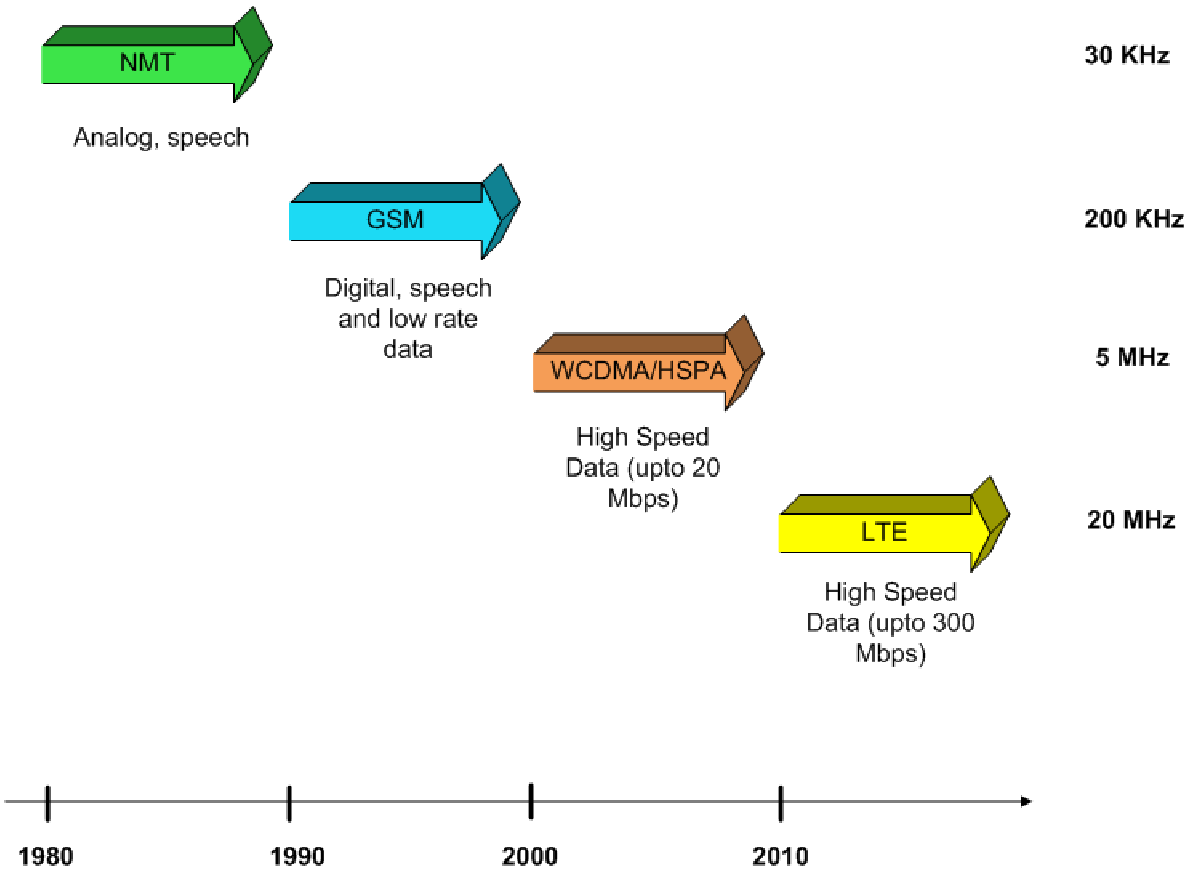

Figure 2.1: Evolution of the wireless system

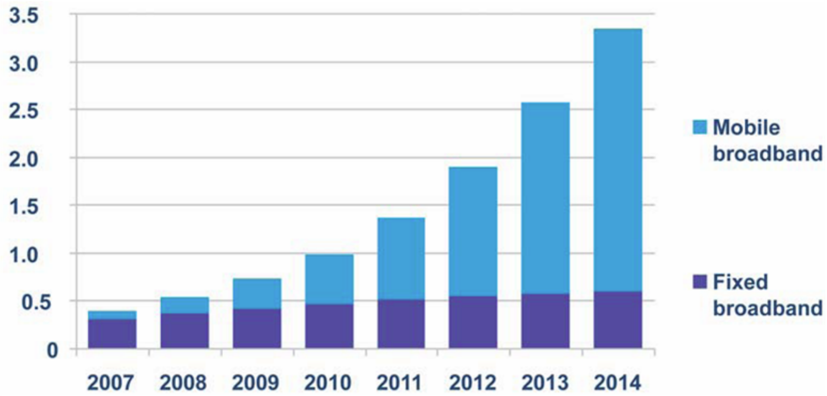

Figure 2.2: Expected Broadband Growth 2007-2014 [1]

(MMS) and content downloads has kick-started the wireless data market, the demand for higher bandwidth video applications such as high definition video sharing, mobile video, multi player real time gaming applications and IPTV are growing quickly. Most mobile operators are offering mobile broadband service, and it is complemented by the PC vendors offering notebooks with built-in HSPA capabilities, that will boost data usage even further. Clearly, data revenues are playing an increasingly important role for operators, driving the need for the higher peak data rates, lower latency, improved system capacity and coverage, reduced operating costs, multi-antenna support, flexible bandwidth operations, seamless integration with existing systems and more spectrally efficient support of data services [11] [12].

Mobile broadband [1] is becoming a reality, as the present internet generation grows accustomed to having broadband access everywhere and not just at home or in the office. It is expected that the broadband subscriptions will reach 3.4 billion by 2014 and the estimate is about 80% of these consumers will use mobile broadband as depicted in the Figure 2.2. Moreover during May 2007, the Packet data traffic overtook voice traffic, based on a world average WCDMA network load as depicted in the Figure 2.3. This was mainly because of the introduction of HSPA in the networks.

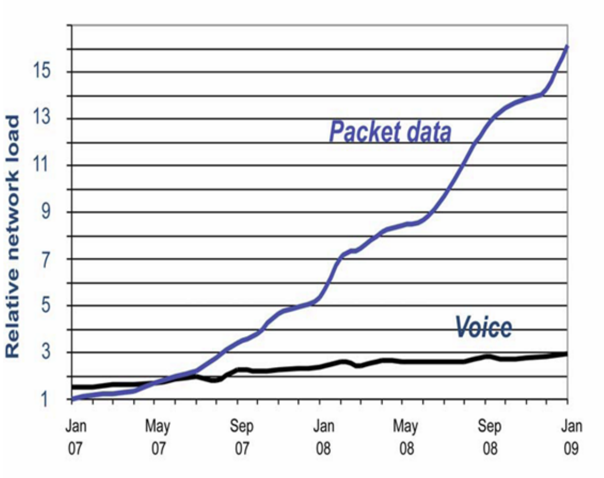

Figure 2.3: Comparision of the packet/voice traffic in the WCDMA networks [1]

Chapter 3

Long Term Evolution (LTE)

This chapter gives a short introduction to LTE. It starts with the LTE performance targets, explains the multiple access technology that forms the basis and finally explains the LTE system architecture.

3.1 LTE Performance Targets

The radio access network architecture forms the basis of every mobile communication technology. LTE is one of the radio access technologies used to access the core network by the mobile. As the name suggests, LTE is considered as a long term answer to overcoming the performance constraints of the present day 3G mobile radio access technology. With these considerations in mind, 3GPP rolled out the LTE track, which is seen as a roadmap towards future 4G systems. The 3GPP design targets of the LTE system as defined in [13] are as follows:

1) **Performance**

The LTE system targets high spectral efficiency of 2.5 bps/Hz in the uplink (UL) and 5 bps/Hz in the downlink (DL). For a 20 MHz spectrum allocation, this corresponds to 50 Mbps and 100 Mbps data rates in the UL and DL respectively, which is ten times more than HSPA Release 6. The best system performance is obtained at 0 - 15 km/h speeds. The LTE system is designed to support user mobility rates as high as 350 km/h. In noise limited scenarios, the system should satisfy the given performance metrics of throughput, spectral efficiency and mobility requirements for a 5 km cell radius. Acceptable degradations in system performance have been defined for cases such as high mobility and larger cell radius. The LTE framework aims to provide services with reduced latency. The latency requirements are split between the control-plane and the user-plane. The control-plane latency refers to the delay in transition from different non-active states to an active state. The user-plane latency refers to the delay in transmitting an Internet Protocol (IP) packet from the terminal to the Radio Access Network (RAN) edge node or vice-versa. LTE also supports enhanced Multimedia Broadcast/Multicast Service (eMBMS) with the possibility to initiate simultaneous voice calls and MBMS.

2) **Spectrum Allocation**

The LTE system is designed to be deployable in the IMT-2000 frequency band, so that the system can co-exist with the legacy GSM and UMTS networks and also support inter operability between different wireless systems. LTE can be deployed in both paired and unpaired spectrum allocations, i.e. the system should support both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes. LTE also supports the bandwidth scalability and can operate in any of the LTE specific allocations of 1.25, 1.6, 2.5, 5, 10, 15 and 20 MHz. The support for bandwidth scalability permits the deployment of the LTE system in the existing 2G/3G spectrum and assists in easier migration towards the higher spectrum allocations. 3GPP release 8 defines 14 and 8 frequency bands for FDD and TDD respectively.

3) **Architecture**

The WCDMA access stratum was redesigned for the LTE to achieve the significantly reduced latency targets. Transition times from idle/dormant states to active state (control plane) are reduced significantly. Similarly, radio access network latency is less than 5 ms in unloaded conditions for the small IP packet (user plane). LTE RAN is an all IP based architecture with support for the conversational and real-time traffic as well. Compared to WCDMA/HSPA, the LTE network consists of a fewer number of network elements/interfaces. The migration from hierarchical to flat network architecture envisaged in LTE reduces network signaling and jitter. LTE base stations known as eNB provide the all-in-one radio access interface between the UE and the Core Network (CN).

4) **Cost**

LTE supports self-organizing networks (SON) capability, offering the ability to automate the network management processes. This intelligent mechanism collects live network data and collectively diagnose a number of issues and fixes them in an optimal way. Thus, the LTE network reduces the operator's network planning and maintenance costs. The idea is to minimize the lifecycle cost of running a network by eliminating manual configuration of equipment at the time of deployment and also to dynamically optimize the radio network performance during operation. The ultimate aim is to reduce the unit cost and retail price of wireless data services.

5) **Security**

A multi-layer, multi-vendor security paradigm is designed for LTE since security challenges are significant in IP networks. Strict user/operator authentication, authorization and auditing, secure data storage, configuration integrity, secure network management and unsolicited traffic protection are viewed as the major targets of LTE network security.

3.2 LTE Multiple Access Technologies

Some of the key features of LTE are multiple access schemes in UL/DL, adaptive modulation and coding, advanced MIMO spatial multiplexing techniques, support for both FDD and TDD mode and Hybrid Automatic Repeat Request (HARQ) mechanisms. LTE multiple access is based on the following techniques [14] [15]:

1) **Orthogonal Frequency Division Multiple Access (OFDMA) [16] [17]**

The DL LTE radio access is based on OFDMA. OFDMA meets the LTE requirement for spectrum flexibility and enables cost-efficient solutions for wide carriers with high peak rates. OFDMA is a well-established technology, for example in standards such as Institute of Electrical and Electronics En-

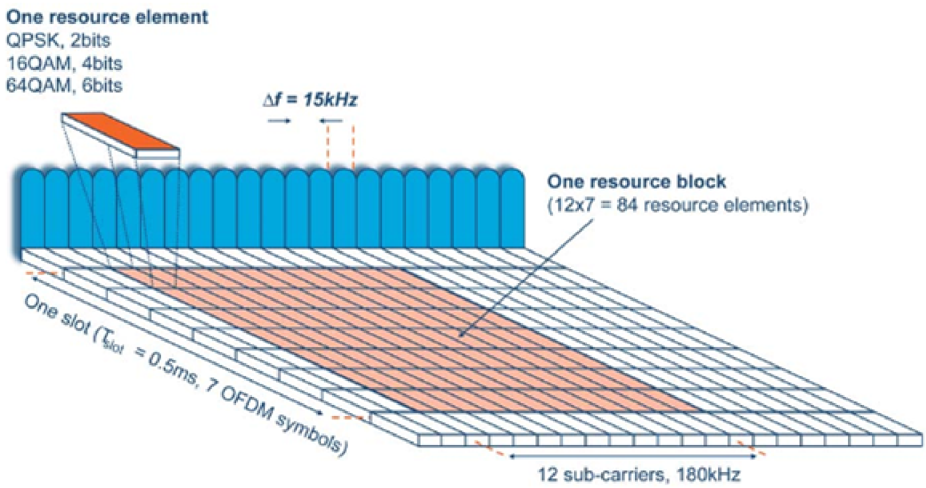

Figure 3.1: LTE downlink physical resource based on OFDMA [2]

gineers (IEEE) 802.11a/b/g, 802.16, HiperLAN-2, Digital Video Broadcast (DVB) and Digital Audio Broadcast (DAB). OFDMA is chosen in the LTE system for DL due to the properties such as good performance in frequency selective fading channels, low complexity of base-band receiver, good spectral properties and handling of multiple bandwidths, link adaptation and frequency domain scheduling, compatibility with advanced receiver and antenna technologies. LTE uses a large number of narrowband sub-carriers for multi-carrier performance transmission. The basic LTE downlink physical resource can be explained as a time-frequency grid, as illustrated in The Figure 3.1. In the frequency domain, the spacing between the sub-carriers is 15kHz. The cyclic prefix is used to maintain orthogonality between the sub-carriers, even for a time-dispersive radio channel.

One resource element carries Quadrature Phase Shift Keying (QPSK), 16QAM (Quadrature Amplitude Modulation) or 64QAM modulated bits. For example with 64QAM, each resource element carries six bits. The Orthogonal Frequency Division Multiplexing (OFDM) symbols are grouped into resource blocks. The resource blocks have a total size of 180kHz in the frequency domain and 0.5ms in the time domain. Each user is allocated a number of so-called resource blocks in the time frequency grid. The more resource blocks a user receives and the higher the modulation used in the resource elements, the higher the bit-rate.

2) **Single Carrier Frequency Division Multiple Access (SC-FDMA)**

The UL LTE radio access is based on a pre-coded version of OFDM called SC-FDMA. The adoption of SC-FDMA for UL is motivated by the lower Peak to Average Power Radio (PAPR) of the SC-FDMA waveform compared to OFDMA. With lower PAPR, efficient radio frequency power amplifier (RFPA) operation can be attained, leading to longer battery life in the handset. SC-FDMA solves this problem by grouping together the resource blocks in a way that reduces the need for linearity and power consumption in the power amplifier. A low PAPR also improves coverage and the cell-edge performance. LTE utilizes single carrier modulation, DFT-spread orthogonal frequency multiplexing and frequency domain equalization.

3) **Advanced Antennas [18] [19]**

Advanced antenna solutions introduced in HSPA Evolution are also used by LTE. Solutions incorporating multiple antennas meet next-generation mobile broadband network requirements for high peak data rates, extended coverage and high capacity. Advanced multi-antenna solutions are vital to achieving these targets. There is not one single antenna solution that can address every deployment scenarios. Consequently, a family of antenna soultions is available for specific deployment scenarios. For example, high peak data rates can be achieved with multi-layer antenna solutions such as 2x2 or 4x4 MIMO, and extended coverage can be achieved with beam-forming. MIMO, one of several forms of smart antenna technology, is the use of multiple antennas at both the transmitter and receiver to improve communication performance. In addition to MIMO (single-user), LTE standard has adopted multi-user MIMO (MU-MIMO). MU-MIMO may be supported by transmitting different data streams to different users within the same resource region via spatial division multiple access (SDMA). MU-MIMO allows a terminal to transmit signal to multiple users and also receive signal from multiple users in the same band simultaneously. As multiple antennas are used at both the transmitter and receiver, it improves the communication performance by providing additional diversity against radio channel fading. MIMO enables features like beam-forming, improved coverage, higher data throughput, higher spectral efficiency, link reliability and diversity.

4) **User scheduling**

A user scheduling algorithm at eNB controls the assignment of resources to the users. The scheduler can take into account both traffic conditions and channel conditions, for example, by scheduling users which have data to transmit or receive and also are in good channel conditions. Advanced scheduling mechanisms at eNB in the frequency and time dimensions decide which resource blocks and how many the user receives at a given point. Scheduling of resources can be done every ms, that means two resource blocks, 180kHz wide and in total one ms in length, called a scheduling block. The scheduling mechanisms in LTE are similar to those used in HSPA and enable optimal performance for different services in different transmission. Different strategies for how to schedule users based on their channel conditions include round robin, maximum rate and proportional fair, which are explained in more details as follows:

In Round robin scheduling, the channel conditions are simply ignored. Users with data to transmit are scheduled one by one and each user receives the equal amount of time to transmit. This strategy provides maximum time fairness to the users, but cannot guarantee any quality of service.

The opposite extreme scheduling strategy is called maximum rate scheduling. Here instead the user with the best instantaneous channel conditions is scheduled. This means that users close to the cell border, who are not in good channel conditions are unlikely to be scheduled at all. Thus, maximum rate scheduling is the least fair to the users, but maximizes the system throughput in case all users have data to transmit. The scheduler in the eNB uses the Channel Quality Indicator (CQI) reports sent by the UE to get the information about the channel quality experienced by the users.

In between of the Round-robin and the maximum rate scheduling lies the Proportional-fair scheduler. Proportional-fair scheduler schedules the user that has the best channel conditions compared to its average channel quality. This way the scheduler maximizes system throughput while still being fair. It also uses CQI reports sent by the UE to get the information about the channel quality experienced by the users.

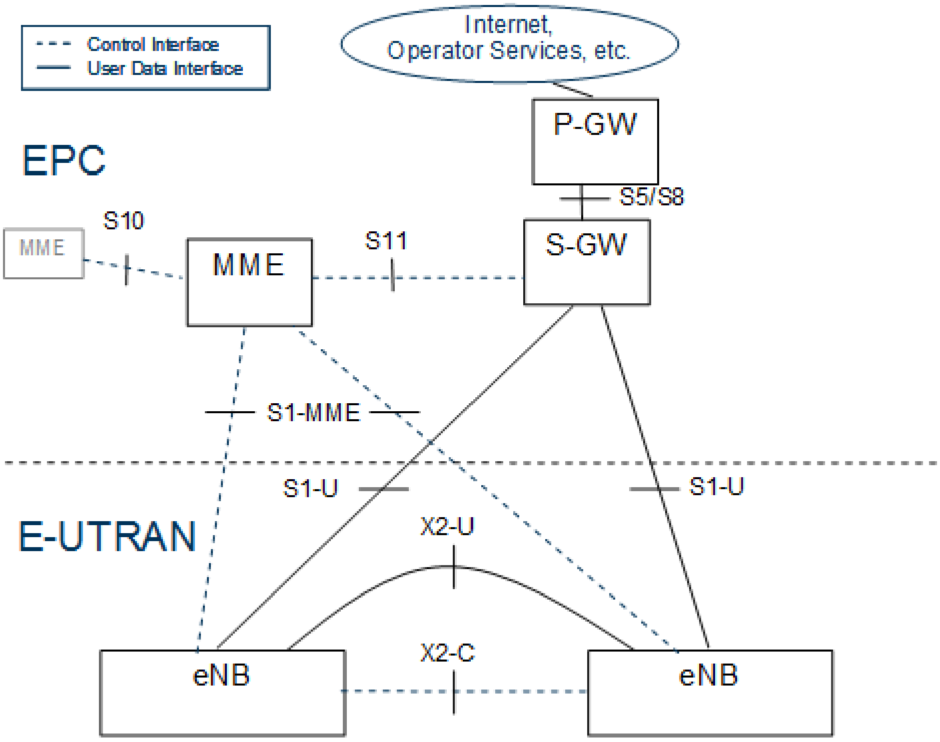

Figure 3.2: Overview of the LTE architecture [3]

3.3 LTE System Architecture

LTE has been designed based on the flat system architecture, as compared to that of the prior hierarchical WCDMA network as depicted in the Figure 3.2. LTE was designed to meet the target requirements such as: packet based network, high throughput, high end user bit rates, improvement in the response times for activation and bearer set-up, improvement in the packet delivery delays and optimized inter-working with other wireless systems.

3.3.1 Logical Elements in LTE

The E-UTRAN consists of eNBs, providing the E-UTRA user plane and control plane protocol terminations towards the UE. The eNBs are connected with each other by a logical interface called the X2 interface. The eNBs are also connected by means of the S1 interface to the EPC, more specifically to the Mobility Management Entity (MME) by means of the S1-MME and to the Serving Gateway (S-GW) by means of the S1-U. It should be noted that in practice the X2 link does not need to be separate from the S1, but that X2 can be realized with the same physical connection and routed via the S-GW. UE accesses the services offered by EPC through eNB. Each of these elements are explained briefly as follows:

1) **User Equipment (UE)**

UE is the device used by the end user for communication, for e.g., smart phone, data card, or can also be embedded to a laptop. UE contains the Universal Subscriber Identity Module (USIM) which is also called the Terminal Equipment (TE). USIM is an application placed into a removable smart card called the Universal Integrated Circuit Card (UICC). UE is used to identify and authenticate the user and to derive the security keys for protecting the radio interface transmission. Functionally, the UE is a platform for communication applications, which communicate with the network for setting up, maintaining and removing the communication link the end user needs. UE also participates in the mobility management functions such as handovers and reporting the terminal location as instructed by the network.

2) **E-UTRAN NodeB (eNB)**

eNB is the only node in the E-UTRAN. eNB is a radio base station controlling all radio related functionality for the set of UE's that are listening to that specific eNB. It acts as a layer 2 bridge between UE and the EPC, by being the termination point of all the radio protocols towards the UE, and relaying data between the radio connection and the corresponding IP based connectivity towards the EPC. The Figure 3.3 depicts the functional split between E-UTRAN and EPC.

The eNB is responsible for many control plane (CP) functions such as the radio resource management (RRM), user plane data delivery, ciphering/deciphering of the user plane data, IP header compression/decompression, scheduling and transmission of paging messages, broadcast information, measurement and measurement reporting configuration for mobility and scheduling. RRM functionality includes radio bearer control, radio admission control, connec-

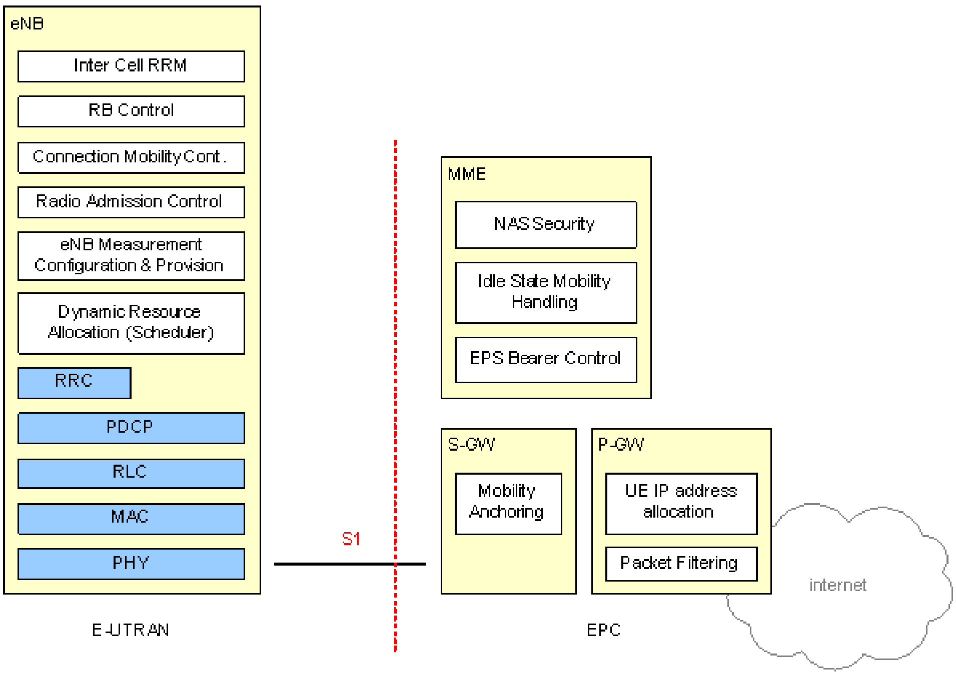

Figure 3.3: Functional split between E-UTRAN and EPC [4]

tion mobility control, dynamic allocation of resources to UEs in both uplink and downlink (scheduling), quality of service (QoS), intereference management and power control.

3) **Mobility Management Entity (MME)**

MME is the main control element in the EPC. Typically, the MME would be a server in a secure location in the operator's premises which operates only in the CP, and is not involved in the path of user plane (UP) data. MME also has a logically direct CP connection to the UE and is used as the primary control channel between the UE and the network. It is mainly responsible for user authentication and security, mobility management, roaming, managing subscription profile and service connectivity.

4) **Serving Gateway (S-GW)**

S-GW is responsible for the functions such as: local mobility anchor point for inter-eNB handover, mobility anchoring for inter-3GPP mobility, lawful interception, packet routing and forwarding, transport level packet marking in the uplink and the downlink and accounting the user. It is also responsible for UP tunnel management and switching. During mobility between eNBs, S-GW acts as the mobility anchor point. The MME commands the S-GW to switch the tunnel from one eNodeB to another. The MME may also request the S-GW to provide tunnelling resources for data forwarding, when there is a need to forward data from the source eNB to the target eNB, during the ongoing radio handover. The mobility scenarios also include changing from one S-GW to another, and the MME controls this change accordingly, by removing tunnels in the old S-GW and setting them up in a new S-GW.

In the connected state, the S-GW relays the data between eNB and P-GW. However, when a UE is in idle mode, the resources in eNodeB are released, and the data path terminates in the S-GW. If S-GW receives data packets from P-GW on any such tunnel, S-GW will buffer the packets, and request the MME to initiate paging of the UE. Paging will request the UE to re-connect, and when the tunnels are re-connected, the buffered packets will be sent on. The S-GW will monitor data in the tunnels, and may also collect data needed for accounting and user charging.

5) **Packet Data Network Gateway (P-GW)**

P-GW is responsible for functionalities such as per-user based packet filtering, lawful interception, UE IP address allocation, transport level packet marking in the downlink, UL and DL service level charging, gating and rate enforcement. P-GW is the router connecting the EPS and external packet data networks. It is the highest level mobility anchor in the system and also is the IP point of attachment for the UE. When a UE moves from one S-GW to another, the bearers have to be switched in the P-GW. The P-GW will receive an indication to switch the flows from the new S-GW. P-GW is responsible for the traffic control functionalities such as gating and filtering. It allocates the IP address to the UE, which is used to communicate with other IP hosts. The allocation of the IP address is done, when the UE requests a Packet Data Network (PDN) connection for getting attached to the network. Thus P-GW uses the Dynamic Host Configuration Protocol (DHCP), to deliver the IP address to the UE. Also, dynamic auto-configuration is supported by the standards. IPv4/IPv6 or both addresses may be allocated depending on the need.

3.4 LTE Radio Access Stratum

LTE Protocol Architecture [5] [20] is divided vertically into an Access Stratum (AS) and a Non-Access Stratum (NAS), and horizontally into a CP and a UP. AS provides services to the NAS and it is a medium used by the UE to transmit the data over the radio interface and the management of the radio interface. Access technique is the way the specific physical media between the UE and the infrastructure is used to carry information. NAS is the part of core network supporting functionality such as the management of user location information, control of network features and services, the transfer (switching and transmission) mechanisms for signalling and for user generated information. The CP includes the application protocol and the signalling bearer for transporting the application protocol messages. It is the one responsible for setting up and controlling UP. The UP includes the data bearers for the data streams. The role of the LTE radio access stratum protocol is to set up, reconfigure and release the radio bearer that provides the means for transferring the EPS bearer. The LTE radio interface protocol layers above the physical layer include layer 2 protocols such as Medium Access Control (MAC), RLC and PDCP. Layer 3 consists of the RRC protocol, which is part of the CP. The protocol layer above (for the CP) is the NAS protocol that terminates in the core network side. LTE radio interface protocol layers made up of the MAC, RLC, PDCP and RRC layers are introduced briefly as below and is also depicted in the Figures 3.4 and 3.5.

3.4.1 Medium Access Control Protocol

The MAC layer maps the logical channels to the transport channels. It is reponsible for functions such as [6] [21]: random access, dynamic user scheduling, priority handling between logical channels of one UE, transport format selection, error correction through HARQ, multiplexing/demultiplexing of RLC Protocol Data Units (PDU) and traffic volume measurement reporting. Ciphering functionality is taken care of by PDCP in LTE, and not by MAC, which was the case for the RLC transparent mode (TM) in WCDMA [22]. Moreover, there is no transport channel type switching as the user data are only transmitted over a single type of transport channel such as the Uplink Shared Channel (UL-SCH) or the Downlink Shared Channel (DL-SCH).

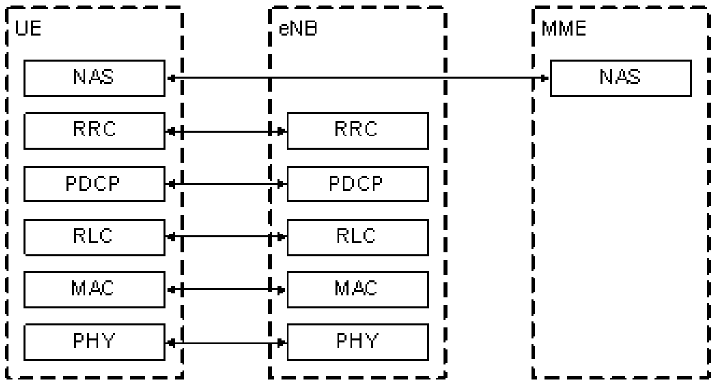

Figure 3.4: LTE control plane [5]

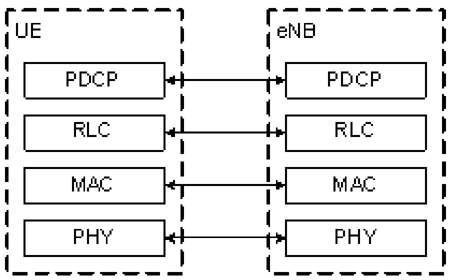

Figure 3.5: LTE user plane [5]

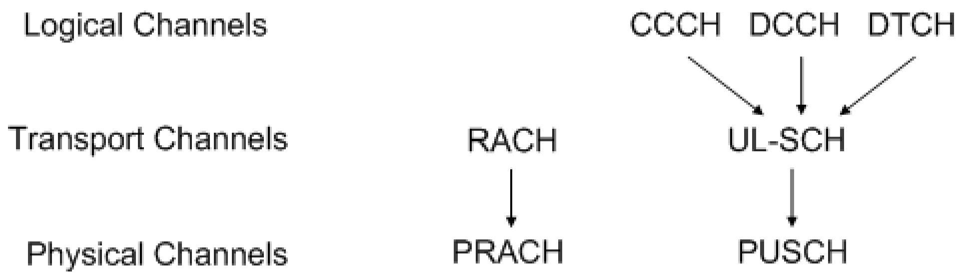

Figure 3.6: Mapping of the uplink logical, transport and physical channels [6]

As depicted in the Figure 3.6, LTE uplink logical channels map to the LTE transport channels. Common Control Channel (CCCH), Dedicated Control Channel (DCCH) and Dedicated Traffic Channel (DTCH) are the existing LTE uplink logical channels. In the uplink direction, all the logical channels are mapped to the UL-SCH. There is no logical channel mapped on the Random Access Channel (RACH), as it does not carry any information above the MAC layer. Similarly RACH maps further to the Physical random access channel (PRACH), whereas, UL-SCH maps further to the Physical uplink shared channel (PUSCH).

Moreover, as depicted in the Figure 3.7, LTE downlink logical channels map to the downlink transport channels. Downlink logical channels such as CCCH, DCCH and DTCH are mapped to the downlink transport channel DL-SCH. Paging Control Channel (PCCH) is mapped to the Paging Channel (PCH), whereas, Broadcast Control Channel (BCCH) is mapped to either Broadcast Channel (BCH) or DL-SCH. Similarly BCH maps further to the Physical broadcast channel (PBCH) in the downlink, whereas, PCH maps further to Physical downlink shared channel (PDSCH).

The MAC layer receives data from the RLC layer as MAC SDUs and it transmits data to physical layer as MAC PDUs. The MAC PDU consists of the MAC header, MAC SDUs and MAC control elements. The MAC control elements carry control information such as: buffer status report, power headroom report, contention resolution procedure information, control of the Discontinuous Reception (DRX) operation and timing advance commands.

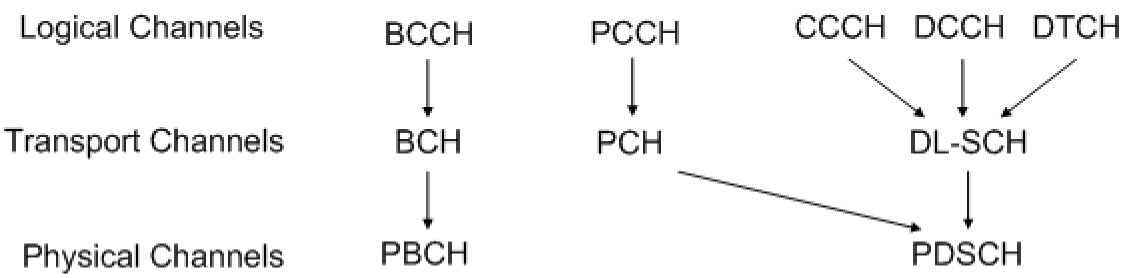

Figure 3.7: Mapping of the downlink logical, transport and physical channels [6]

3.4.2 Radio Link Control Protocol

The RLC layer is responsible for the functions such as [23] [24]: transferring the SDUs received from higher layers, i.e. from RRC or PDCP to the lower MAC layer, error correction with ARQ, concatenation/segmentation, in-sequency delivery, duplicate detection, protocol error handling. Ciphering functionality is taken care of by PDCP in LTE, and not by RLC, which was the case for the non-transparent RLC mode (AM or UM) in WCDMA [22]. Moreover, re-segmentation before RLC retransmission is enabled.

RLC Modes of operation

The RLC supports three different modes of operation [15]:

1) **Transparent Mode (TM)**

In TM mode, the RLC does not add any headers to the delivered or received data on a logical channel. The TM mode of operation is only suited for services that are not sensitive to delivery order. Thus from the logical channel only BCCH, CCCH and PCCH can be operated in TM mode.

2) **Unacknowledged Mode (UM)**

The UM Data are segmented or concatenated to suitable size RLC PDUs and then the UM header is added. Header is used for in-sequence delivery of data which might be received out of sequence due to HARQ operation in lower layers. The RLC UM header includes the sequence number for facilitating in-sequence delivery and duplicate packet detection. Logical channel DTCH can be operated in UM mode.

3) **Acknowledged Mode (AM)**

RLC AM mode is typically used for best effort data transfer. Automatic Repeat Request (ARQ) procedure, responsible for the transmission/retransmission of the packets are only performed by an AM RLC entity. RLC AM mode supports the retransmission of the PDU's, if lost due to the operations in the lower layer. Moreover, re-segmentation is also supported to fit the physical layer resources available for retransmission. Logical channels DCCH or DTCH can be operated in AM mode.

The RLC layer receives data from the PDCP layer and stores it into the transmission buffer. Based on the resources available, data is either segmented or concatenated. An RLC PDU can either be a RLC data PDU or a RLC control PDU. RLC data PDUs are used by TM, UM and AM RLC entities to transfer upper layer data. RLC control PDUs are used by AM RLC entity to perform ARQ procedures. STATUS PDU is a RLC control PDU, which is used by the receiving AM RLC entity to inform the transmitting AM RLC entity about AMD PDUs that are received successfully, and AMD PDUs that are detected to be lost by the receiving AM RLC entity. The transmitting side of an AM RLC entity can receive a negative acknowledgement for an AMD PDU or a portion of an AMD PDU. When receiving a negative acknowledgement for an AMD PDU or a portion of an AMD PDU by a STATUS PDU from its peer AM RLC entity, the transmitting side of the AM RLC entity shall retransmit that PDU.

An AM RLC entity can also poll its peer AM RLC entity in order to trigger the RLC status report from the peer AM RLC entity. An AM RLC entity sends the RLC status report in the form of a STATUS PDU, in response to the poll from its peer AM RLC entity in order to provide the positive and/or negative acknowledgements for the received RLC PDUs. Triggers to initiate the RLC status reporting include polling from the peer AM RLC entity and detection of a missing RLC data PDU. When the RLC status reporting has been triggered by the transmitter, the receiving side of an AM RLC entity shall send the RLC status report, if the timer t-StatusProhibit is not running. If the t-StatusProhibit is running, the RLC STATUS is sent upon the expiry

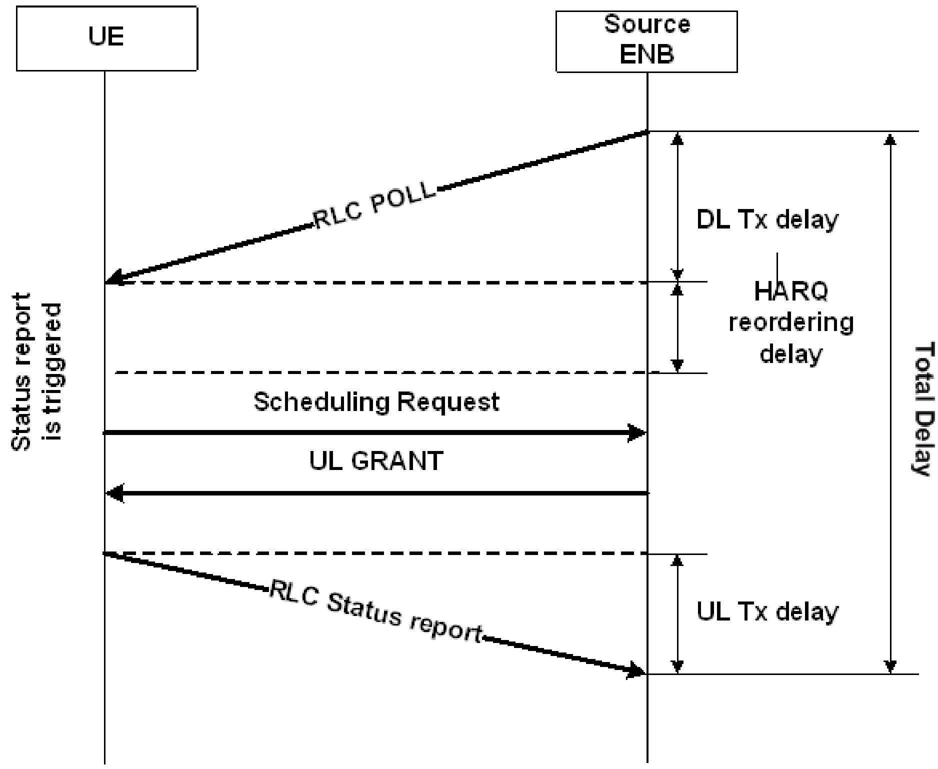

Figure 3.8: RLC Polling PDU/Status Report exchange [7]

of the timer. RLC UE receiver t-StatusProhibit timer is used by the UE's receiving side of an AM RLC entity in order to prohibit the transmission of the STATUS PDU. The Figure 3.8 depicts the RLC polling / Status report exchange mechanism, without the t-StatusProhibit timer.

3.4.3 Packet Data Convergence Protocol

The PDCP layer [25] [26] is located above the RLC layer. RLC and PDCP have interactions especially at the time of re-establishment, which is performed, e.g., at handover. The key functionalities of the PDCP include header compression and decompression, transfer of user data, in-sequence delivery of upper layer PDUs at PDCP re-establishment procedure for RLC AM, duplicate detection of lower layer SDUs at PDCP re-establishment procedure for RLC AM, retransmission of PDCP SDUs at handover for RLC AM, ciphering and deciphering, timer-based SDU discard in uplink, transfer of control plane data.

The PDCP layer receives PDCP SDUs from the NAS/RRC and after ciphering and other actions, the data are forwarded to the RLC layer. Correspondingly, in the receiving side the data are received from the RLC layer. The PDCP layer is responsible for the data forwarding functionality in connection with the intra LTE handover events for the DL. The PDCP layer at the source eNB will forward the non-delivered packets to the target eNB. In the UL, PDCP retransmits all the packets to the target eNB, which have not been successfully acknowledged by lower layers, as the RLC is reset and MAC HARQ buffer is flushed at handover. Both of these techniques in UL/DL will ensure that no data is lost in connection with the handover event between the LTE eNBs.

Header compression and corresponding decompression of the IP packets is based on the Robust Header Compression (ROHC) protocol. The ROHC protocol is specified by the IETF. On PDCP, the ROHC functionality can be used for all IP data on the DRBs both in RLC AM and UM mode. The ROHC is an optional feature in the specification, and thus the network can decide to turn the feature on or off in the UE [8] depending on its own and the UEs capabilities.

The key difference to WCDMA is that now all user data go via the PDCP layer, as PDCP is responsible for the ciphering of the data. The ciphering is applied to the data part of the PDCP data PDUs on both control and user plane. PDCP control PDUs are not ciphered. Signaling Radio Bearers (SRB) use integrity protection in addition to ciphering, i.e., the possibility to identify the source of a control message is who it claims to be.

The timer based SDU discard in the UL is an optional feature configured by the network. All PDCP SDUs being queued for more than the configured time are discarded to prevent transmission of outdated information. The timer could be seen as a simplistic Active Queue Management (AQM) function. To disable the function, the timer value is set to infinity.

The PDCP Status reporting is also an optional feature that can be configured by the network. The Status reports can be sent from the UE or to the UE. The main function of the Status report is to decrease the amount of data transmitted over the air due to PDCP level retransmissions after a

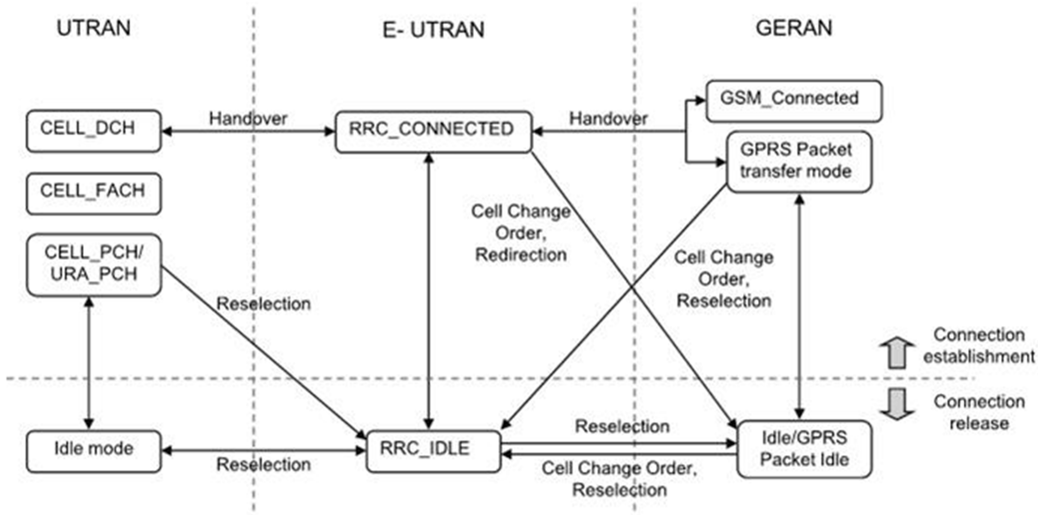

Figure 3.9: E-UTRAN RRC States and state transitions among 3GPP Systems [8]

handover. The uplink and downlink status reports are configured separately, i.e. only either or, none, or both can be used. The optional PDCP Status report includes the First Missing PDCP SN in the receiver, optionally a bitmap consisting of information on out-of-sequence reception from the RLC at re-establishment in the same receiver.

3.4.4 Radio Resource Control Protocol

The RRC layer functionality includes [8]: broadcast of system information, RRC connection control, inter/intra RAT mobility, cell selection/reselection, measurement control, paging, transfer of dedicated control information for the specific UE, security key management, self-configuration and self-optimisation.

Contrary to the UMTS, UE states in LTE are simplified significantly to only two states, i.e., RRC-CONNECTED and RRC-IDLE, depending on whether the RRC connection has been established or not. In the RRC-IDLE state, the UE listens to the paging channel to track the incoming calls, acquires the system information and also performs neighboring cell measurement and cell (re)selection. LTE network configures UE specific Discontinuous Reception (DRX) in the UE [27]. In the RRC-CONNECTED state, the UE transfers data to the network and also receives data from the network. For this, the UE monitors control channels that are associated with the shared data channel to determine if data are scheduled for the specific UE and provides channel quality feedback to the eNB. Moreover the UE also performs the neighboring cell measurements and measurement reporting based on the configuration configured by the eNB. UE mobility i.e. handover is controlled by the network in RRC-CONNECTED state. The Figure 3.9 compares the mobility support between E-UTRAN, UTRAN and GSM Enhanced Data Rates for GSM Evolution Radio Access Network (GERAN). As the CELL-FACH state in UTRAN is considered a very short period, a direct transition from UTRAN CELL-FACH to E-UTRAN RRC state is not supported.

Chapter 4

Data forwarding

LTE supports network controlled handover, based on measurements performed and reported by the UE. The source eNB may forward the unacknowledged data to the target eNB, during the ongoing handover for the specific UE. Moreover, the source eNB may also forward fresh data arriving over S1 interface to the target eNB. The source eNB discards all unacknowledged downlink RLC PDUs, as RLC is reset after the handover. Correspondingly, the source eNB also does not forward the downlink RLC context to the target eNB. Moreover, the target eNB is responsible to retransmit the forwarded data to that UE, once the connection between the UE and the target eNB is established. The target eNB does not have to wait for the completion of forwarding from the source eNB before it begins transmitting packets to the UE.

The data forwarding is a function, the network can choose to perform to ensure a lossless handover for a Data Radio Bearer (DRB). The forwarding can be done on both RLC AM and RLC UM bearers, but only the PDCP RLC AM bearers have support on PDCP level for SN continuity. For the PDCP RLC UM bearers the sequence numbers are reset, and the data on lower layers is discarded at the re-establishment procedure done at handover. This may lead to data loss, if there was data in the buffers that had not yet been received in the receiver side. Moreover, also for the RLC AM bearers the data on lower layers is discarded at the re-establishment procedure done at handover.

The forwarded data at the source eNB is made up of: (1) the data that is already sent on the air but not yet acknowledged by the UE, (2) the data in the PDCP queue which is not sent yet and (3) the data that has newly

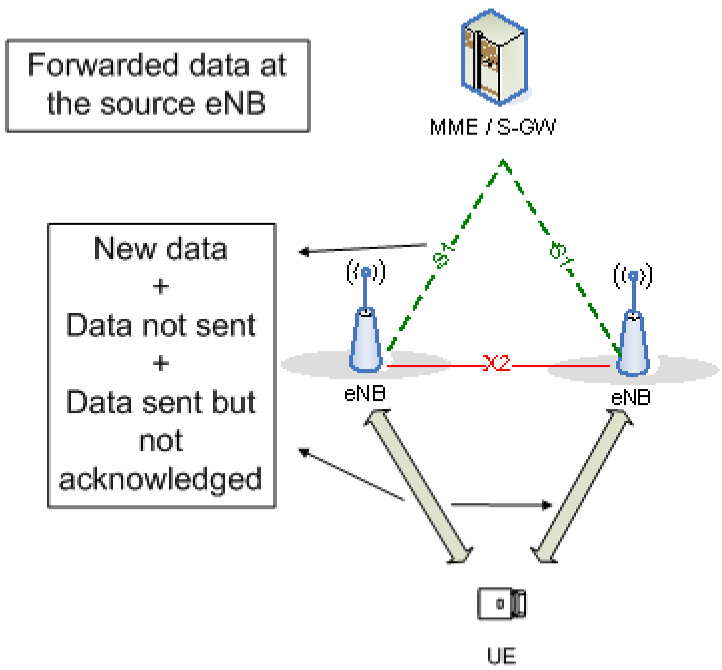

Figure 4.1: Forwarded data at the source eNB during handover

arrived at PDCP from the upper layers. The first two types of data is forwarded in the form of PDCP buffer from the source eNB to the target eNB once the handover is initiated. On the contrary, the newly arriving data at PDCP of the source eNB during the ongoing handover is forwarded until the path switch happens after the handover from the source eNB to the target eNB. The Figure 4.1 depicts the forwarded data buffer at the source eNB.

4.1 Mobility Management

LTE supports the active mode mobility management in which the eNBs are making the handover decisions autonomously without involving the MME/S-GW. The required handover information is exchanged between the eNBs via the X2 interface. The MME/S-GW is notified with a handover complete message after a new connection is established between the UE and the target eNB. Upon reception of this message, the MME/S-GW performs the path switch. There is no temporary buffering of user data at the MME/S-GW. The benefit of this handover solution is the decreased signaling load on S1

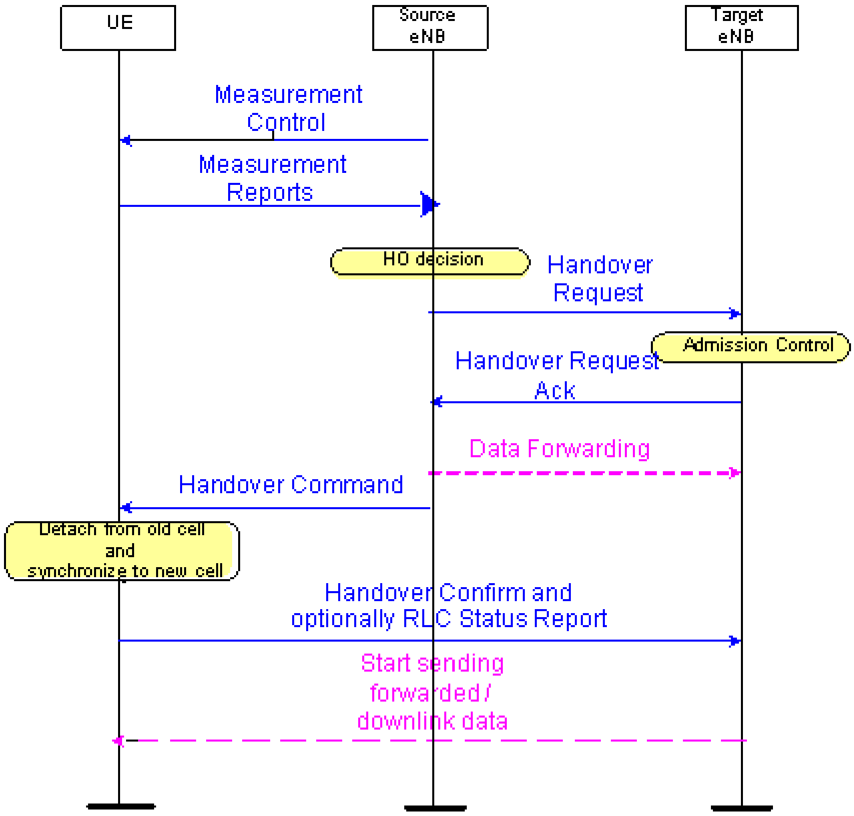

Figure 4.2: Intra LTE handover with data forwarding [4]

interface. During the handover, the protocol end points that are located in the eNBs are required to be moved from the source eNB to the target eNB. In LTE, the RLC/MAC protocols (ARQ/HARQ window states) are reset at handover.

The main steps of the handover procedure as depicted in the Figure 4.2 are briefly explained as follows [4]:

1) The handover is triggered by the UE that sends a Measurement Report (MR) to the source eNB, indicating the stronger signal strength of the target eNB compared to the existing source eNB. The source eNB makes the handover decision based on the MR and RRM information.

2) Handover negotiation phase starts by sending the Handover Request from the source eNB to the target eNB.

3) The target eNB makes the handover decision, based on the available radio resources and also prepares L1/L2 for the Handover and responds to the source eNB with the Handover Request Ackowledgement, which provides information for the establishment of the new radio link. The information also includes the new Cell Radio Network Temporary Identity (C-RNTI).

4) The source eNB transfers all the necessary information to the UE in the Handover Command. From this instant, the source eNB may stop sending and receiving data over the air and it may forward the DL data to the target eNB. The source eNB forwards the RLC SDUs that are buffered, but not yet acknowledged. In other words, partially transmitted SDUs at the HARQ/ARQ layers will be forwarded along with the buffered and not yet transmitted SDUs, which also includes all the incoming SDUs from the GW.

5) The UE establishes the new radio connection to the target eNB on receiving the Handover Command. This procedure involves detaching from the old cell, synchronizing to a new one, obtaining timing advance and uplink allocation. During this time (Detach Time) there is no radio connectivity to the system. The UE sends the Handover Confirm message informing the target eNB about the success of handover.

6) The target eNB initiates the data path switching by sending the Handover Complete to the MME/SAE Gateway. The UE location information is updated at the MME/SAE Gateway, after receiving the Handover Complete message and the target eNB performs the path switching, after which packets are directly sent to the target eNB.

7) The MME/SAE Gateway confirms the path switching with the Handover Complete Acknowledge message. After receiving this message, the target eNB sends the Release Resource indication to the source eNB, so that the source eNB can flush its forwarded DL data buffer that might have been stored for the case of the handover fallback.

The quality of service during the handover is based on the detach time, during which the UE is not connected to the system, the delay of the forwarded packets and the delay difference between the direct path and the forwarded path. The goal of the thesis is to reduce the delay of the forwarded packets, by decreasing the amount of the forwarded data that is already received by the UE. The idea is to decrease the amount of discarded DL packets both at the target eNB and UE.

4.2 Data Forwarding Mechanism

Data forwarding is introduced in 3GPP LTE Release 8 specification [4] and [25]. The specification [25] covers the UE side of the protocol, however, PDCP is also used in the network side at handover to perform data forwarding between the eNBs over the X2 interface. More details on the X2 messaging, such as the SN Status Transfer, are described in [28]. During the ongoing handover, the source eNB forwards all the unacknowledged PDCP SDUs to the target eNB. Data forwarding is also explained briefly in [29] and [30]. [29] explains the need of packet forwarding in LTE and also shows how forwarding helps to improve the TCP throughput. It also deals with the problem of out of order packet delivery during the handover and proposes a solution to the problem. In [30], authors provide the overview of LTE, handover procedure and also evaluate the impact of forwarding on the user connection.

The thesis proposes various techniques to improve the packet forwarding mechanism as specified in 3GPP LTE Release 8 standards by reducing the number of PDCP packets that are required to be forwarded from the source eNB to the target eNB. PDCP and RLC protocols are used to ensure the lossless handover functionality. The RB is configured to use the RLC protocol in AM, and the corresponding PDCP mode for DRB. Each PDCP PDU is given to RLC for transmission. The RLC AM functions so that each RLC PDU sent out must be acknowledged by the receiver side to the transmitter side. ACKs are sent upon a POLL request from the transmitter, and upon t-Reordering timer expiry at the receiver side, in case the t-StatusProhibit timer is not running and there are missing PDUs. If the t-StatusProhibit is running, the RLC STATUS is sent upon the expiry of the timer.

RLC entity receives the RLC SDUs from upper layer and sends RLC PDUs to its peer RLC entity via lower layers. Similarly, RLC entity delivers the RLC SDUs to upper layer and receives RLC PDUs from its peer RLC entity via lower layers. One RLC PDU can contain a various number of PDCP SDUs,

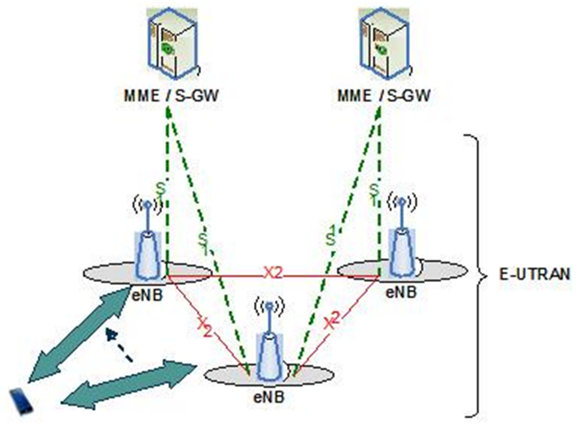

Figure 4.3: Data forwarding during the Intra-LTE handover from the source eNB to the target eNB [4]

or segments thereof, based on the instantaneous link bitrate. Upon reception of an ACK for the whole RLC SDU, the RLC protocol must indicate the successful delivery of the higher layer PDU to the upper layer, i.e., to the PDCP transmitter. To ensure a lossless handover, the PDCP transmitter should not discard the SDUs from it's buffer before PDCP has received the indication of the successful delivery from the RLC transmitter.

Below the RLC layer, the HARQ protocol at the MAC level is responsible for the transmission and retransmission of the packets. LTE link layer uses transmissions/retransmissions at both the MAC and RLC layer, of which, the MAC HARQ retransmissions are comparatively faster than the RLC ARQ retransmissions. The HARQ is usually configured so that there is a high probability of the data transmitted from the source eNB to be successfully received by the UE without involving RCL retransmissions.

During the handover, all the PDCP SDUs that have not been ACKed by the lower layer are forwarded to the target eNB from the source eNB. This mechanism of forwarding is specified in 3GPP LTE Release 8 specification. The Figure 4.3 depicts the intra LTE handover between the source eNB and the target eNB. The source eNB may start the data forwarding after it receives HO request acknowledgement from the target eNB. The UE moves to the target eNB after receiving the handover command from the source eNB. When in the target cell, UE sends the handover confirmation message to the target eNB. At this stage, UE may also transmit the PDCP Status report, if so configured by the source eNB. After reception of the PDCP Status report, the target eNB can discard the PDCP SDUs that have already been received by the UE in the source cell. If the UE is not configured to transmit the PDCP Status report to the target eNB, the target eNB will transmit all the the forwarded SDUs. The UE may drop some of these SDUs received from the target eNB, if the UE has already received the SDUs from the source eNB before the handover.

4.3 Problem with the Data Forwarding

A problem with the existing data forwarding mechanism is that the source eNB is unaware of the latest information, of what data the UE has received and what it has not received. During the handover, all the unacknowledged PDCP SDUs are forwarded to the target eNB by the source eNB via X2 interface. Many of these PDCP SDUs, that are forwarded to the target eNB have been already successfully received at the UE, and so are either dropped at the target eNB or at the UE. This results in inefficient data forwarding mechanism between the source eNB and the target eNB, which unnecessarily increases the load on the data link connecting the two eNB's and also on the air interface between the target eNB and the UE. Since the RLC ACK procedure depends on the POLL and the t-Reordering settings, it could be that many of those SDUs have been already successfully delivered to the UE, and would not need to be forwarded to the target eNB.

4.4 Existing Work to Improve the Data Forwarding Mechanism

Based on the 3GPP LTE Release 8 specification, all the unacknowledged PDCP SDUs are forwarded from the source eNB to the target eNB. One of the 3GPP contributions [31], compares this forwarding scheme with the no-forwarding scheme, which may also be the possible implementation choice for the deployment scenarios. In the no-forwarding scheme, the source eNB discards all stored PDCP SDUs. The lost PDCP SDUs will not be recovered by RAN protocol but by the upper layer retransmission protocol such as TCP layer. The author concludes that the forwarding scheme of the RLC SDUs is an essential feature to guarantee the good TCP performance during the handover. Moreover, [31] also states that there is unnecessary data forwarding from the source eNB to the target eNB, due to late RLC status reporting. The 3GPP contribution recommends the need of some optimizations on this aspect, such as the event triggered RLC status reporting at the source eNB. Several solutions to solve the problem of inefficient data forwarding mechanism at hand, have been presented in the form of the 3GPP contributions, and have also been patented, such as, in [7], [32], [33] and [34]. All these recommended solutions are further analysed in the following section.

One of the 3GPP contributions [7] proposes two solutions to improve the data forwarding mechanism. The first solution is that the source eNB polls the UE, just after receiving the MR from the UE. But, it concludes claiming that the time between the source eNB receives the MR, until the source eNB sends the handover command, is not always enough, to poll the peer UE RLC and in return, receive the RLC status report.

As another solution, [7] and [32] both suggest to send the RLC status report along with the MR in the uplink. The source eNB configures the measurements in the UE, as specified in [8]. It is the responsibility of the UE to send the MR, whenever the conditions configured by the source eNB is satisfied. Based on [8], measurement events such as Event A3 (Neighbour becomes offset better than serving), Event A4 (Neighbour becomes better than threshold) and Event A5 (Serving becomes worse than threshold1 and neighbour becomes better than threshold2) can trigger the source eNB to perform the handover of the UE to the target eNB. During the ongoing handover, the source eNB may also perform the data forwarding to the target eNB. As per the solution, it suggests to send the RLC status report along with the MR, which has a higher chance of trigerring the handover between the intra LTE eNBs. The problem with the suggested solution is that MR is sent by the UE RRC, whereas RLC status report is sent by the UE RLC. It means that whenever the UE RRC is sending the the MR, which has a higher chance of trigerring the handover, the UE RRC also needs to inform the UE RLC to send the RLC status report. Presently the 3GPP LTE RRC standard [8] does not support such inter layer messages. Moreover, such inter layer messages are not acknowledged as the part of the 3GPP UE standard. Lastly, the solution will also require the new RLC status message trigger in the 3GPP RLC standards. Presently based on the 3GPP LTE RLC specifications [23], RLC is supposed to send the RLC status report only due to triggers such as the polling from its peer AM RLC entity, detection of a missing RLC data PDU. To sum up, the proposed solution requires changes in the 3GPP LTE Release 8 specifications of RRC [8] and RLC [23]. So far, the aforementioned solution have not been accepted in the 3GPP to be part of the specification.

A further solution introduced in [33], suggest to send the PDCP status report, instead of the RLC status report to the source eNB, before the UE detaches from the source eNB. This solution is similar to the last solution as discussed above and will require changes to the 3GPP LTE Release 8 specifications of RRC [8] and PDCP [25], and has so far not been accepted to be part of the specification. Lastly, a further solution proposed in [34] is similar to the one proposed in [7].

4.5 Proposed Solutions to Improve the Data Forwarding Mechanism

During the ongoing handover, all the data present in the PDCP buffer at the source eNB needs to be forwarded to the target eNB. The thesis proposes the techniques to improve the data forwarding mechanism by reducing the amount of data forwarding between the source eNB and the target eNB, which are as follows:

1) Change the UE polling frequency based on the downlink data rate

The proposed solution tries to decrease the data that is already sent over the air but not yet acknowledged by the UE. Increasing the UE polling frequency allows the source eNB to be as up to date to the UE reception state as possible, and thus reduces the data buffer at the PDCP of the source eNB.

The basic idea with the suggested technique is that the source eNB will poll the UE more often, when the UE specific downlink data rate is high. On the contrary, the source eNB will poll the UE less often, during the lower downlink data rate. The proposed method minimizes the data being forwarded from the source eNB to the target eNB, as the source eNB will be as up to date to the UE reception state as possible, and thus reduces the number of unacknowledged PDCP SDUs to be forwarded to the target eNB.

There exists a tradeoff between the PDCP data forwarding buffer size in the eNB and the uplink RLC status load. When the source eNB polls the UE more often to decrease the PDCP buffer size, the uplink RLC status load increases. Similarly, when the source eNB polls the UE less often then the PDCP buffer size increases but the uplink RLC status load decreases.

The UE polling frequency can be changed based on the RLC configuration parameter of the source eNB such as the pollByte or the pollPDU. PollByte or pollPDU is used by the source eNBs transmitting side of each AM RLC entity to trigger a poll for every "pollByte" of data send or every "pollPDU" PDUs sent to the UE. Moreover, along with this parameter change, the source eNB should also configure the UEs t-StatusProhibit timer, in such a way that it allows the UE to send the RLC status report. The t-StatusProhibit timer is used by the UEs receiving side of an AM RLC entity in order to prohibit the transmission of the RLC STATUS PDUs.

Please note that, the proposed solution does not consider the ongoing handover, while changing the UE polling frequency. The problem with the proposed solution is that, we are increasing the UE polling frequency, even though there is no improvement in the data forwarding efficiency, in the scenarios when the handover is not ongoing. This results in higher RLC status load in the uplink due to RLC status reports sent from the UE to the source eNB at all times.

2) Change the UE polling frequency during handover based on the downlink data rate

This solution is a slight variant from the last solution, and also tries to decrease the data that is already sent on the air but not yet acknowledged by the UE. It is different than the last proposed solution, as the UE polling frequency is changed, just before the ongoing handover, based on the downlink data rate. The advantage with the solution is that it does not result to the higher uplink RLC status load, when the handover is not ongoing. UE polling frequency can be changed based on the RLC configuration parameter of the eNB such as change the value of the pollByte or the pollPDU, as explained in the last solution. A tradeoff between the PDCP data forwarding buffer size in the eNB and the uplink RLC status load still exists as in case of the last proposed method.

3) Stop user scheduling after the MR is sent

This solution tries to decrease the data that has newly arrived at PDCP from upper layers. Once the UE sends the MR to the source eNB, the source eNB may decide to perform the handover to the target eNB. If the source eNB is going to perform the handover, then based on the suggested solution, it also stops scheduling DRBs from that specific UE till the handover is performed. Please note that the SRBs of that specific UE may still be scheduled. In the meantime, the source eNB can also schedule the other UE's present in the existing cell.

4) Stop downlink user scheduling and allow limited uplink user scheduling

This solution is a slight variant from the last solution, and also tries to decrease the data that has newly arrived at PDCP from the upper layers and also partly reduces the data that is already sent on the air but not yet acknowledged by the UE. It is different than the last proposed solution, as the source eNB only stops downlink DRBs user scheduling for the UE undergoing the handover, but allows the limited uplink user scheduling. The limited uplink user scheduling allows the UE to send the RLC status report to the source eNB in the uplink. On receiving the RLC status report, the source eNB can drop the acknowledged PDCP SDUs, and thus decrease the amount of data that needs to be forwarded to the target eNB.

Chapter 5

Simulation Results

5.1 Problem Formulation

Various data forwarding mechanisms from the source eNB to the target eNB in LTE are studied as part of the thesis. The goal is to propose and evaluate various techniques that reduce the data forwarding as specified in 3GPP Release 8 specification. In this chapter, we will first introduce the system model for the simulation and then present the simulation results based on the proposed techniques to improve the data forwarding during handover in LTE.

5.2 Simulation Environment and System Model

The LTE simulator developed at Ericsson Research was used in the thesis to implement and simulate various techniques to improve the data forwarding mechanism. As shown in the Figure 5.1, simulator consist of protocol layers such as a FTP client/server, TCP/IP, PDCP, RLC and MAC.

The FTP client sends the FTP Request to the corresponding FTP server and waits for the FTP response to be sent. Once, the FTP client receives the data from the underlying TCP layer, it schedules another request or just terminates. Note that, in our data forwarding DL simulation, the FTP client is located in the UE, whereas as the FTP server is in the Core Network. Requests are always sent from the FTP client to the FTP server and the FTP reponse the other way around. The mean reading time is the time between

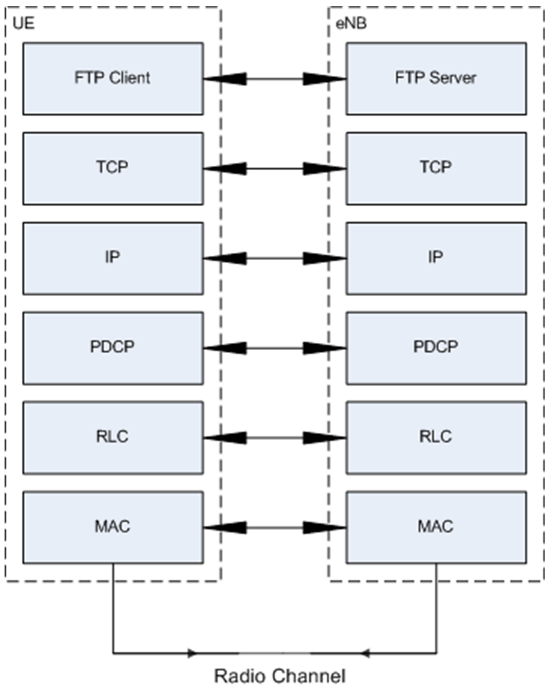

Figure 5.1: Simulator Protocol Stack

two consecutive FTP requests, which is fixed in the simulations. Object bit rate is calculated based on the data rate which the FTP client experiences.

The TCP provides reliable data transfer between two the TCP entities by means of an ARQ protocol. Furthermore, TCP performs congestion control to avoid overloading underlying links. TCP is connected to an underlying IP entity, and to the FTP client/server in the upper layer.

The IP layer accepts data from a higher layer, encapsulates it into IP packets and forwards it to the lower layer. The peer IP entity receives these IP packets, extracts the payload and forwards the packet to the TCP layer. Functionality of PDCP, RLC and MAC layers are already explained earlier in the the chapter "Long Term Evolution".

The simulator is run in a simplified mode, which does not include the physical layer functionality of the adaptive modulation and coding (AMC), i.e. the modulation rate is not changed based on the UE experienced radio conditions. The scope of the thesis is to decrease the amount of data forwarding which is the responsibility of PDCP, so not including the AMC functionality is a fair assumption. The transport format size is selected randomly, however giving a mean downlink data rate of 75 Mbits per sec.

The system is being modelled for a single user, who does a FTP download of a 100 MB file, 50 times, while being connected to the eNB. The simulation is controlled in such a way that, although the UE is static, the handover occurs every 4 s. Data is required to be forwarded from the source eNB to the target eNB during the ongoing handover. The RLC mechanism is based on the polling configuration parameter pollByte, having the value of 3000 KB. The used traffic model is FTP with a fixed file size. The FTP traffic model is supposed to give the most data forwarding gain compared to other traffic models like web browsing.

The parameters used in the simulation, which are defined in [4] [6] [23] are as shown in the Table 5.1.

1) Transmit time interval (TTI) refers to the length of an independently decodable transmission on the radio link, which is 1 ms in LTE.

2) Measurement report delay is the assumed fixed delay in the simulation

Parameter	Value
Transmit time interval (TTI)	0.001 s
Measurement report delay	0.03 s
Handover interruption delay	0.03 s
Handover interval	4 s
Round trip delay between FTP server and eNB	0.02 s
Path Switch Delay	0.01 s
X2 interface delay	0 s
RLC eNB transmitter pollPDU	0
RLC eNB transmitter t-PollRetransmit	0.045 s
RLC eNB transmitter maxRetxThreshold	infinite
RLC UE receiver t-Reordering	0.04 s
RLC UE receiver t-StatusProhibit	0 s
DL HARQ channel bleps	0.1,0.03,0.01,0.005,0.001
DL HARQ channel failure probability	0.0001
UL HARQ channel bleps	0.1,0.03,0.01,0.005,0.001
DL/UL HARQ channel fixed transmission delay	4 subframes
HARQ RTT	8 subframes

Table 5.1: LTE environment simulation parameters

for sending the Measurement report from the UE to the source eNB till the UE receives the Handover command from the source eNB. It is made up of: (a) optimistic Measurement report transmission delay on the HARQ channel - 0.005 s, (b) Handover negotiating delay between the source eNB and the target eNB - 0.02 s and (c) optimistic Handover Command transmission delay on the HARQ channel - 0.005 s

3) Handover interruption delay is the assumed fixed delay for the handover between the source eNB to the target eNB. It is made up of: (a) Resynchronisation delay caused by the UE trying to synchronise with the target eNB - 0.02 s and (b) scheduling delay caused by the scheduler at the target eNB to schedule the UE, to send the uplink Handover Complete message - 0.01 s

4) Handover interval is the fixed time after which handover happens again.

5) Round trip delay between the FTP server and the eNB is the minimum delay of the round trips between the internet (FTP server) and eNB.

6) Path Switch Delay is the delay due to switching of the path between the MME and the eNB, when the UE has changed the cell from the source eNB to the target eNB.

7) X2 interface delay is the delay caused while forwarding the data between the two eNBs during the handover.

8) RLC eNB transmitter pollPDU is used by the eNB's transmitting side of each AM RLC entity to trigger the poll for every "pollPDU" PDUs.

9) RLC eNB transmitter t-PollRetransmit is used by the eNB's transmitting side of each AM RLC entity to retransmit the poll, if the UE does not respond.

10) RLC eNB transmitter maxRetxThreshold is used by the eNB's transmitting side of each AM RLC entity to limit the number of retransmissions of an AMD PDU.

11) RLC UE receiver t-Reordering timer is used by the UE's receiving side of an AM RLC entity in order to detect the loss of the RLC PDUs at the lower layer. If t-Reordering is running, t-Reordering shall not be started additionally, i.e. only one t-Reordering per RLC entity is running at the given time.

12) RLC UE receiver t-StatusProhibit timer is used by the UE's receiving side of an AM RLC entity in order to prohibit the transmission of the STATUS PDU.

13) DL/UL HARQ channel bleps is the block error probabilities for the HARQ transmission attempts.

14) DL HARQ channel failure probability is the probability that the transmission attempt results in the HARQ failure, i.e., in the packet loss. This may e.g. be due to a NACK=>ACK error.

15) DL/UL HARQ channel fixed transmission delay is the minimum transmission delay experienced by all DataUnits. An additional variable delay is added based on the simulated number of HARQ transmission attempts.

16) HARQ RTT is the round trip delay time on the HARQ channel.

5.3 Simulation Results

3GPP LTE Release 8 specification [4] specifies the forwarding mechanism for handling the packet forwarding during the handover. Accordingly, all the PDCP SDUs that have not been ACKed by the lower layer are forwarded to the target eNB from the source eNB. In our simulations, the source eNB polls the UE at a constant rate, irrespective of the ongoing handover scenarios. This mechanism is taken as a base method to compare the performance with the technique proposed in [7] and other techniques proposed as a part of the thesis. The performance criteria is based on the PDCP buffer size required for the data forwarding, user experienced object bitrate and uplink RLC status load. The techniques that are implemented in the LTE simulator are as shown below:

1) Reference case in which no RLC report is sent with the MR and the UE polling frequency is kept constant

2) Send the RLC status report along with the MR [7]

3) Change the UE polling frequency based on the downlink data rate

4) Change the UE polling frequency during handover based on the downlink data rate

5) Stop user scheduling after MR is sent

6) Stop downlink user scheduling and allow limited uplink user scheduling

The value of pollByte is kept constant to 3000 KB in the above mentioned techniques such as: (1) reference case, (2) Send the RLC status report along with the MR, (3) Stop user scheduling after MR is sent and (4) Stop downlink user scheduling and allow limited uplink user scheduling.

Whereas, the value of pollByte is 280 KB in case of the proposed methods on "Change the UE polling frequency based on the downlink data rate". Moreover, the value of pollByte varies based on the handover in case of the proposed technique "Change the UE polling frequency during handover based on the downlink data rate". The value of pollByte is 3000 KB, when the handover is not ongoing. On the contrary, the value of pollByte is decreased to 280 KB, when the handover is ongoing.

The AM RLC entity of the source eNB triggers a poll for every "pollByte" of the data transmitted to the UE. The value of pollByte is derived based on the downlink data rate (75 Mbps) and period (0.03 sec), as shown below:

pollByte = Data Rate * Period

where, period (0.03 s) is the Measurement report delay that is the time between the UE sends the MR to the source eNB to the time UE receives Handover Command from the source eNB.

As shown in the Figure 5.2, the proposed method on "Change the UE polling frequency based on the downlink data rate" performs not only better than the reference case but also better than the method on "Send the RLC status report along with the MR" proposed in [7]. It reduces the amount of data forwarding at the PDCP source eNB by nearly 50% compared to the reference case, in which UE is polled with the constant polling frequency.

In [7], author claims that the time between the source eNB receives the MR, until the source eNB sends the handover command, is not always enough, to poll the peer UE RLC and in return, receive the RLC status report. However, based on the simulation performed using the similar parameters in the LTE simulator, the thesis proposes that the time between the source eNB receives the MR, until the source eNB sends the handover command, is enough to poll the peer UE RLC and in return receive the RLC status report. Based on the results, the thesis proposes the technique of increasing the UE polling frequency during the ongoing handover, compared to the time when the handover is not ongoing. Simulation results prove that the proposed method gives better performance in terms of more efficient data forwarding mechanism compared to the one proposed in [7].

As a part of the performed simulations, the RLC pollByte is changed based on the downlink data rate. The value of the pollByte parameter is decreased when the UE has a higher downlink data rate, whereas, the value of the pollByte parameter is increased when the UE has a lower downlink data rate. As the value of the pollByte is decreased when the UE has a higher data rate, the polling will be performed more often, and in turn the UE will respond with RLC status reports more often. As a result, the source eNB is updated with the more precise UE reception state. Thereby, decreasing the amount of data required to be forwarded from the source eNB to the target eNB. Similarly, when the UE is experiencing lower data rate, the value of pollByte is increased, resulting in fewer RLC status reports from the UE to the source eNB. The source eNB does not need to poll the UE more often during the lower downlink data rate as the PDCP buffer size is already smaller in the

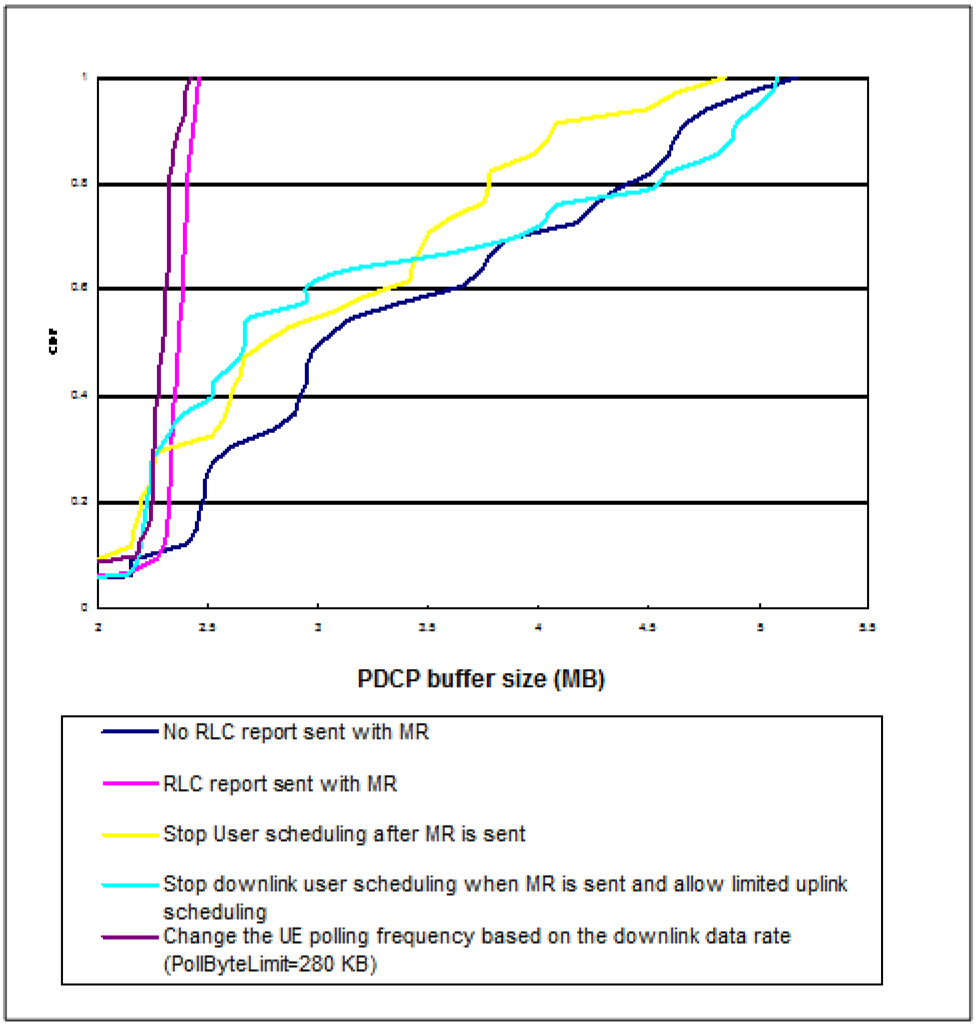

Figure 5.2: CDF for PDCP Buffer Size comparing the proposed methods with existing ones

source eNB. Moreover, this decreases the unwanted load in the uplink due to few RLC status reports sent from the UE to the source eNB.

Based on the simulation results, the other two methods that are proposed in which "Stop user scheduling after MR is sent" and "Stop downlink user scheduling and allow limited uplink user scheduling" also prove to be more efficient as far as data forwarding efficiency is concerned compared to the reference case in which "RLC report is not sent with the MR". It reduces the PDCP buffer size by 18% compared to that the reference case. But they are not as good as the method on "Change the UE polling frequency based on the downlink data rate".

Based on the above results, "Change the UE polling frequency based on the downlink data rate" proved to be the best technique out of the ones listed to improve the data forwarding efficiency. Possible variants of this technique will be discussed subsequently. As depicted in the Figure 5.3, the two proposed variants of changing the UE polling frequency are compared in terms of their data forwarding efficiencies. In one of the method, eNB changes the UE polling frequency based on the downlink data rate even when the handover is not ongoing i.e. the value of pollByte is fixed as 280 KB. The problem with this solution is that the source eNB will poll the UE more often based on the downlink data rate, even though the data forwarding is not ongoing. In the second method, the source eNB only changes the UE polling frequency only during the ongoing handover and is based on the downlink data rate i.e. the value of pollByte used is 3000 KB in non handover scenarios and decreased to 280 KB during the handover. The advantage of this method compared to the former one is that it gives the RLC status load gain of 80%. Moreover, the Figure 5.3 shows that it also performs better than the second method, in terms of data forwarding efficiency. Based on these results, the thesis proposes that the LTE network to be configured in such a way that it uses higher value of pollByte during the time when handover is not ongoing and use the lower value of pollByte during the ongoing handover scenarios. It helps to gain not only in terms of data forwarding efficiency but also decreases the RLC status load.

As shown in the Figure 5.4, results are generated based on increasing the UE polling frequency during the handover and are then compared in terms of data forwarding gains. The idea is to poll the UE at higher frequency, to decrease the data forwarding PDCP buffer size at the source eNB. The highest

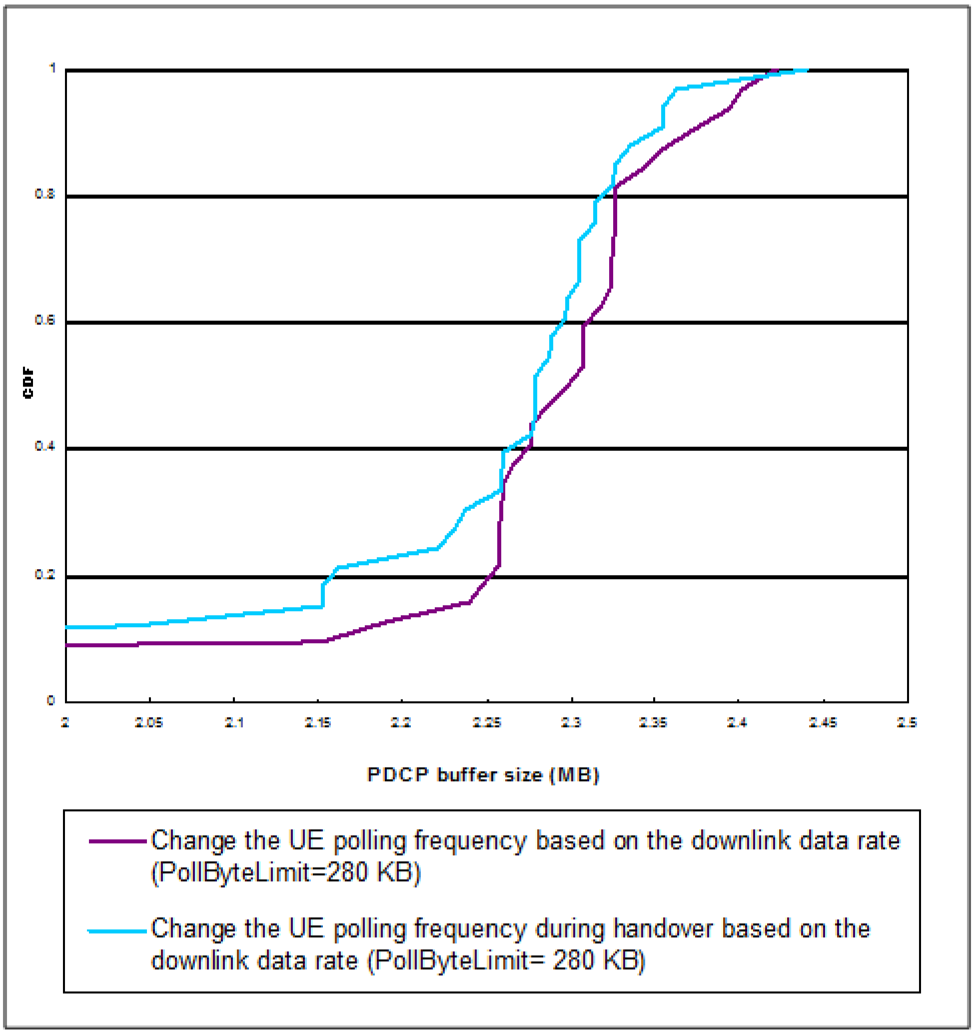

Figure 5.3: CDF for PDCP Buffer Size comparing the the two proposed variants of changing the UE polling frequency

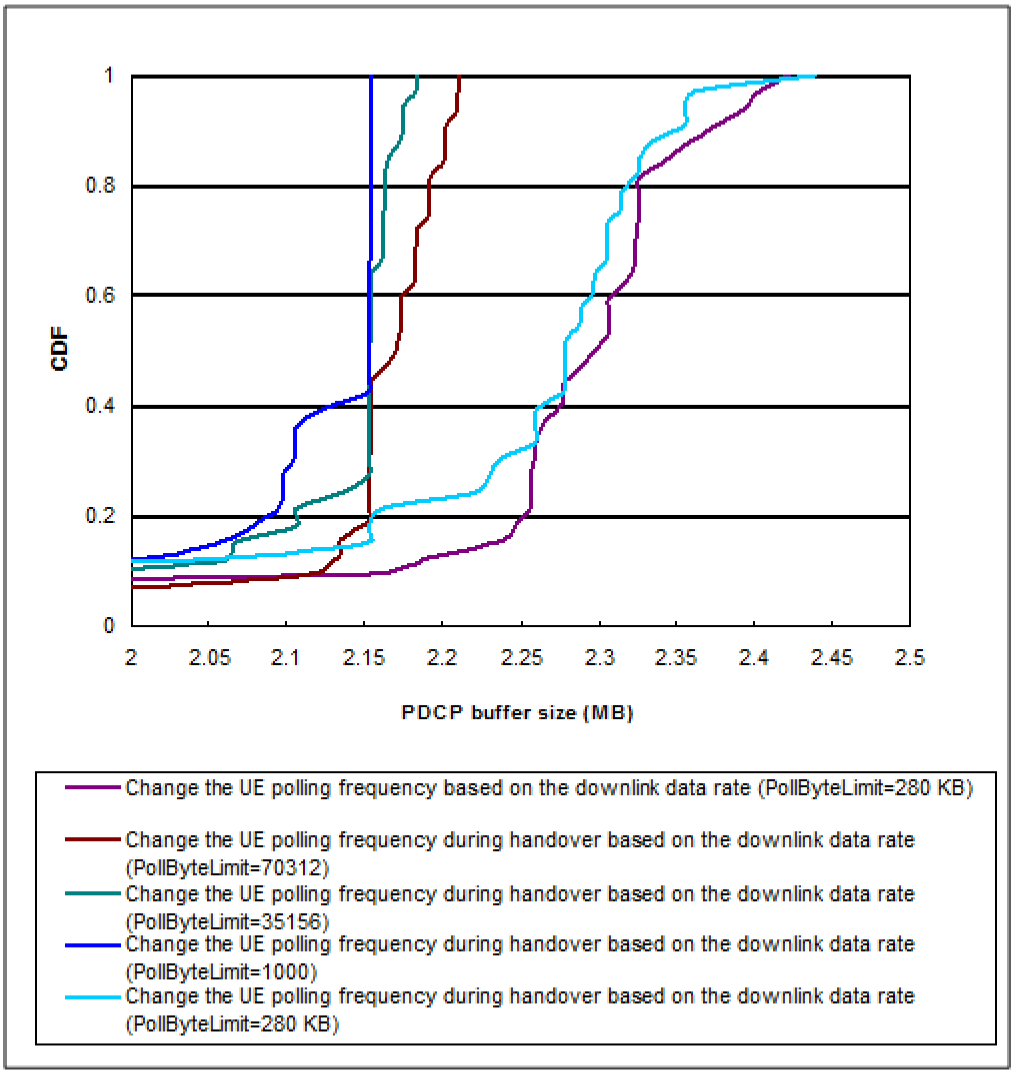

Figure 5.4: CDF for PDCP Buffer Size based on increasing the UE polling frequency

data forwarding gain is achieved in case of "Change the UE polling frequency during handover based on downlink data rate (PollByteLimit=1000 Bytes)". It maps to polling the UE every TTI during the ongoing handover scenarios. In this method, the achieved gain in terms of the reduced PDCP buffer size at the source eNB, during the data forwarding is around 7% compared to the method in which PollByteLimit is 280KB, and is set based on the downlink data rate during handover. But the problem with this method is it increases the RLC status load by 21%. The gain of increasing the polling frequency during the handover is to reduce the data forwarding PDCP buffer size at the source eNB, but the problem with increasing the polling frequency is the increase in the higher RLC status load due to more RLC Status reports sent from the UE to the source eNB. To sum up, the thesis recommends the LTE network to use the optmised value of pollByte, as there exist a tradeoff between the PDCP data forwarding buffer size in the eNB and the uplink RLC status load.

All the proposed data forwarding techniques were compared with the reference case data forwarding technique in terms of the data forwarding PDCP buffer size gain and RLC status load in the uplink. The proposed techniques shall also be compared to the reference case data forwarding technique in terms of user experienced object bit rate. Higher object bit rate influence the better end user experience. The Figure 5.5 compares the object bit rates of all the techniques, and the proposed technique of "Change the UE polling frequency based on the downlink data rate" gave the best object bit rate. It gave better results by around 2% higher object bitrate compared to the reference data forwarding mechanism.

Various techniques of data forwarding were compared in terms PDCP buffer size at the source eNB, uplink RLC status load and user object bit rate. Based on the above results to improve the data forwarding mechanism in the LTE Release 8 networks, the thesis recommends the LTE network to poll the UE more frequently during the ongoing handover scenarios, compared to the case when handover is not ongoing. Based on the simulation results, this proposed technique proves to be the most efficient in terms of lower PDCP buffer size at the source eNB, lower uplink RLC status load and higher user object bit rate. The thesis also recommends the LTE network to use the optimised value of pollByte. Network designer may consider the tradeoff between the PDCP data forwarding buffer size in the eNB and the uplink RLC status load, while determining the value of the pollByte.

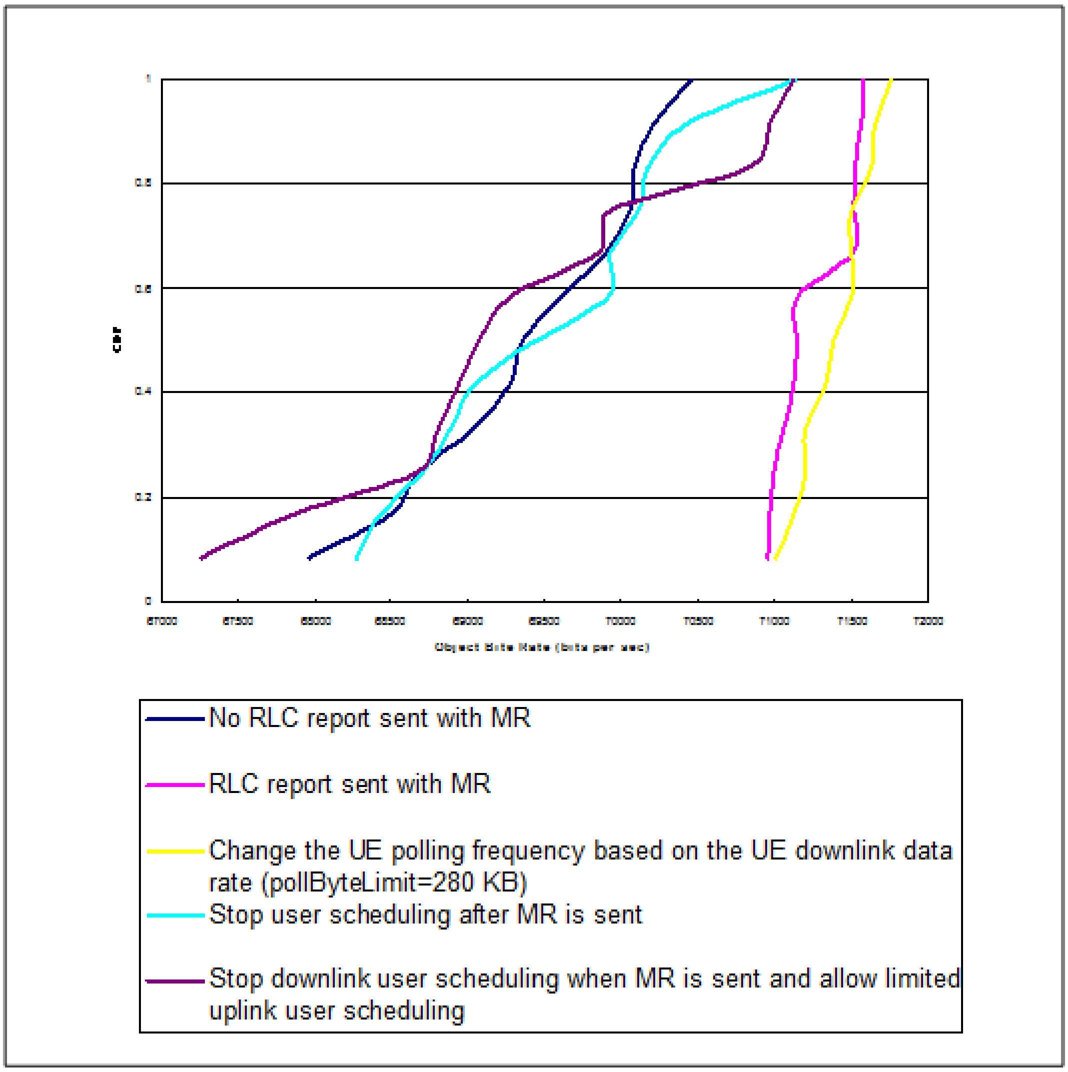

Figure 5.5: CDF for Object bit rate

Chapter 6

Conclusion

At handover between the base stations in LTE, data is forwarded from the source eNB to the target eNB. The mechanism for handling the packet forwarding is specified in the 3GPP LTE Release 8 specifications. Various techniques are proposed and also evaluated to improve the packet forwarding mechanism during the handover by reducing the amount of forwarded data in the downlink. Performance criteria considered for evaluating these techniques include the PDCP buffer size at the source eNB, uplink RLC status load and user object bit rate.

The thesis recommends the LTE network to poll the UE more frequently during the ongoing handover scenarios, compared to the case when handover is not ongoing. Based on the simulation results, this proposed technique proves to be the most efficient in terms of lower PDCP buffer size at the source eNB, lower uplink RLC status load and higher user object bit rate. The thesis also recommends the LTE network to use the optimised value of pollByte. Network designer may consider the tradeoff between the PDCP data forwarding buffer size in the eNB and the uplink RLC status load, while determining the value of the pollByte.

Chapter 7

Future Work

The LTE network behaviour for the downlink data transmission during the ongoing handover was studied as a part of the thesis. In the future, it would also be good to study the LTE UE behaviour for the uplink data transmission during the ongoing handover. UE is repsonsible for the retransmissions of data that is not acknowledged by the source eNB to the target eNB in the uplink. It would be interesting to study and verify whether the same kind of techniques can be applied for uplink as used in case of downlink to improve the packet retransmission efficiency. This may reduce the PDCP buffer size during the ongoing handover at the UE, resulting in less data required to be retransmitted to the target eNB. The applied technique may reduce the radio channel uplink load between the UE and the target eNB.

The simulator is presently run in a simplified mode, which does not include the physical layer functionality of AMC. UE experiences the mean downlink data rate as 75 Mbits per sec. In future, it would be good to include the physical layer, which changes the modulation and coding at the eNB based on the CQI reported by the UE.

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